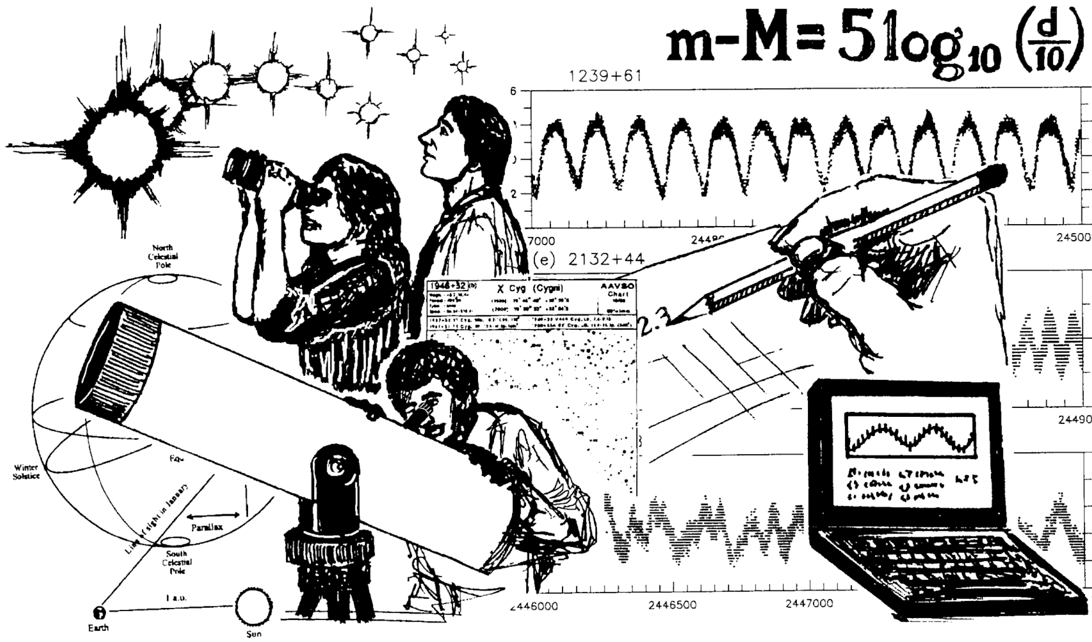
AAVSO Variable Star Astronomy

Web version of Hands-On Astrophysics



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Project Co-Directors

Janet Akyüz Mattei
The American Association of Variable Star Observers

John R. Percy
Erindale Campus, University of Toronto

Curriculum Author

Donna L. Young
Lead Educator: Chandra EPO/SAO/NASA

The American Association of Variable Star Observers, Cambridge, Massachusetts, U.S.A.

AAVSO Variable Star Astronomy

49 Bay State Road
Cambridge, MA 02138
U.S.A.

Phone: 617-354-0484
Fax: 617-354-0665
e-mail: aavso@aavso.org
World Wide Web: http://www.aavso.org

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AAVSO VARIABLE STAR ASTRONOMY

Project Staff

Janet Akyüz Mattei	Project Co-Director
John R. Percy	Project Co-Director
Donna L. Young	HOA Manual Author
Michael Saladyga	Project Facilitator Assistant Editor & Graphics
Karin Hauck	Production, Design, & Layout Assistant Editor
Lynn Matthews Anderson	Production Editor Cover Art and Graphics

Astrophotography
John Chumack

Charts

Charles E. Scovil	Editor and Production
Kerriann Malatesta	Coordinator, Asst. Editor
Sara J. Beck	Finder Slide Production

Contributors

Jeffrey S. Lockwood	Grant Foster
Janet A. Mattei	Michael Saladyga

Slide/Print Production

Michael Saladyga	Coordinator, Editor
Sara J. Beck	Associate Editor
Alan Asadorian	Slide Production

Dorian Color Lab, Inc., Arlington, MA

David Landry	Print Production

Software

Grant Foster	VSTAR
Michael Saladyga	HOAENTER, HOAFUN

Teacher Consultants

Kristine Larsen	Judith Stoltz
Jeffrey S. Lockwood	Donna L. Young
Sharmi Roy	

Video Production

David Tucker	Executive Producer
Todd Hallam	Producer and Director

Equipment and Facilities:
Sheridan College, Oakville, Ontario, Canada
The Edit Sweet, Toronto, Ontario, Canada

Web Site Development
Scott Battaion
The Wright Center for Innovative Science Education, Tufts University, Medford, MA

Artwork

Lynn M. Anderson	Miranda Read
Lola Chaisson	Michael Saladyga

Teacher Workshop Participants/Evaluators

Workshop 1 (1994)

Henry Bouchelle	Ardis Maciolek
M. Kathleen Cochrane	L. Rob Ochs
Daniel Francetic	Michael Richard
Michael Hoke	Sharmi Roy
Carl Katsu	Edward Ruszczyk
James Kernohan	Gary Sampson
Paul Lee	Judith Stoltz
Jeffrey S. Lockwood	Sallie Teames

Workshop 2 (1995)

B. Steven Albert	Kristine Larsen
Roger Bennatti	George Leonberger
Glenn F. Chaple, Jr.	Francis M. Mikan
John Clarke	Parker E. Moreland
Mary Dombrowski	S. Hughes Pack
Philip Dombrowski	Brian Rogan
Gita Hakerem Foster	Joseph Wesney
Alan Hirshfeld	Donna L. Young

Education Advisory Board

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Erindale Campus, University of Toronto
Robert F. Tinker
Technical Education Research Ctr, MA
Charles A. Whitney
Harvard-Smithsonian Center for Astrophysics, Cambridge, MA
Anne G. Young
Rochester Institute of Technology, NY

Proofreading
Elizabeth O. Waagen

Software testing

David J. Sworin	Branko Miskov
Gene Hanson	John E. Isles

Special thanks to:
Gerhard L. Salinger
Program Director, Instructional Materials Development, Directorate for Education and Human Resources, National Science Foundation

Additional thanks to:
Eric Chaisson
The Wright Center for Innovative Science Education, Tufts University, Medford, MA

The Department of Astronomy, and Erindale Campus, University of Toronto, and their students: Winnie Au, Laura Syczak, Monica Milanowski, Matt Szczesny, Sarah Thompson, and Lawrence Yu.

Marvin E. Baldwin
Chair, AAVSO Eclipsing Binary Committee

Neil F. Comins, *University of Maine at Orono*

John E. Isles, *Plymouth, MI*

Initial AAVSO-HOA Web Site Developers
Leora Aimee Hurwitz
Elena Khan
William Mackiewicz

Organizations
National Science Foundation
American Association of Variable Star Observers
University of Toronto, Erindale Campus, Ontario, Canada
Sheridan College, Ontario, Canada
Fondation Dudley H. Wright, Geneva, Switzerland
Harvard-Smithsonian Center for Astrophysics
Harvard College Observatory
Amateur Telescope Makers of Boston
National Aeronautics and Space Administration
Space Telescope Science Institute
Comité de Liaison Enseignants Astronomes, France
Astronomical Society of the Pacific

AAVSO Staff Contributors

Lynn M. Anderson	Karuna Kramer
Sara J. Beck	Kerriann Malatesta
Grant Foster	Janet A. Mattei
Tanja Foulds	Michael Saladyga
Karin Hauck	Elizabeth O. Waagen
Shawna Hutchings	Theodore Wales

HANDS-ON ASTROPHYSICS VIDEOS

Writers	**Film Crew**
John R. Percy	David Tucker, *Executive Producer*
Janet A. Mattei	Todd Hallam, *Producer/Director/Editor*
Michael Saladyga	Mark Dury, *Camera/Lighting*
Todd Hallam	Karl Dipelino, *Audio*
David Tucker	Sylvie Charland, *Narrator*

Video Animations
Dana Berry, *The Wright Center for Innovative Science Education, Tufts University, Medford, MA*

Additional photography

Terence Dickinson	Jack Newton

Featured in HOA Videos
Mary Dombrowski
Amateur Astronomer, High School Student, Glastonbury, CT
Christopher Sousa
Amateur Astronomer, High School Student, Glastonbury, CT
Glenn F. Chaple, Jr.
Amateur Astronomer, Science Teacher, Townsend, MA
Gerald P. Dyck
Amateur Astronomer, Music Teacher, Assonet, MA
Peter Garnavich
Astronomer, Harvard-Smithsonian Center for Astrophysics, MA
Owen Gingerich
Astronomer/Historian, Harvard-Smithsonian Center for Astrophysics
Martha L. Hazen
Astronomer and Archivist, Harvard College Observatory, MA
Imelda B. Joson
Amateur Astronomer, Editor, Burlington, MA
Robert P. Kirschner
Astronomer, Harvard-Smithsonian Center for Astrophysics, MA
Stephen P. Knight
Amateur Astronomer, Farmer, Waterford, ME
Brewster La Macchia
Amateur Astronomer (photometrist), Andover, MA
David W. Latham
Astronomer, Harvard-Smithsonian Center for Astrophysics, MA
Wayne M. Lowder
Amateur Astronomer, Physicist, Valhalla, NY
Brian G. Marsden
Astronomer, Harvard-Smithsonian Center for Astrophysics, MA
Janet A. Mattei
AAVSO Director, Astronomer, Cambridge, MA
E. Talmadge Mentall
Amateur Astronomer, Editor, Lynn, MA
Mario Motta
Amateur Astronomer, Cardiologist, Lynnfield, MA
John R. Percy
Astronomer, University of Toronto, Ontario, Canada

Additional Video Participants

Edwin Aguirre	David Kochuk	Terri Olsen
Thomas Applin	Michael Mattei	John Reed
Lee Budryk	Scott Melanson	Robert Simmons
Robert Collara	Andrea Motta	**HOA Teachers**
Carol Dombrowski	Joyce Motta	Kristine Larsen
Philip Dombrowski	Justin Motta	Sharmi Roy
T. Helga Dyck	Melissa Motta	Judith Stoltz
Scott Kenyon	Richard Nugent	Donna L. Young

Preface

Through the years, the American Association of Variable Star Observers (AAVSO) has been a source of information and guidance to students who decide to study variable stars for class or science fair projects. The idea to develop a formal curriculum using the AAVSO's unique variable star database, however, came about when I attended "An Education Initiative in Astronomy" workshop, supported by NASA, in Washington, DC, in February of 1990. The opportunities, objectives, strategies, and recommendations that were discussed at that workshop, along with the presentation by Dr. Bassam Z. Shakhashiri, then Director of the National Science Foundation's Education Division, who suggested that we as astronomy educators have the best tools to attract the attention and imagination of students, other teachers, and the public, provided the impetus and ideas for *Hands-On Astrophysics*.

My colleague John R. Percy, a leading advocate of astronomy education for decades, had been using AAVSO variable star observations in many projects for his students at the University of Toronto. Inspired by the Washington, DC, workshop, Dr. Percy and I, with the strong endorsement of the AAVSO Council, decided to develop together a curriculum—*Hands-On Astrophysics*—based on our many years of experience in guiding students, and utilizing many decades of AAVSO variable star observations.

Variable stars are stars that change in brightness, and these changes in brightness help us understand the nature and evolution of stars and galaxies. The study of variable stars is particularly suited to science, math, and computer education. Students can observe variable stars with binoculars, telescopes, and even with the unaided eye, and then can analyze the changes in brightness of the stars they observe by using the over 600,000 observations and the computer programs provided with *Hands-On Astrophysics*. As students discover the unique qualities and the oddities of a star's behavior, they can find out more about "their star" through further research in the library and via the Internet.

With members in 45 countries, the AAVSO is the largest organization in the world dedicated to variable stars, and with over 8.5 million variable star observations from its founding in 1911 to the present, the AAVSO is custodian of the world's largest database on variable stars. Many variable star observing groups around the world submit their observations to the AAVSO to be part of the AAVSO International Database, so they can be used by researchers and educators around the world. AAVSO members and observers range in age from eight to over 90, and come from all walks of life, but they all have one thing in common: a love of and curiosity about variable stars. These dedicated amateur astronomers have provided the unique component of the *Hands-On Astrophysics* curriculum—real data which can be used by students, teachers, and amateur and professional astronomers alike to discover the secrets of the stars, including our own Sun.

All components of the *Hands-On Astrophysics* curriculum were designed with the discovery process in mind. Our intention in offering this curriculum to you is to help students acquire fundamental science skills and to develop an understanding of basic astronomy concepts, to provide interdisciplinary connections, and to take students through the whole scientific process. It is our hope that while having fun in working with real data, students will develop more sophisticated math and computer skills. We further hope that *Hands-On Astrophysics* will foster among both students and teachers a love of and interest in one of the most fascinating branches of science—astronomy.

Hands-On Astrophysics is not just for students and teachers: it has been developed for everyone who is interested in astronomy and in learning more about the wonders and workings of the universe. HOA materials are suitable for amateur astronomers who wish to learn more about the fascinating nature of variable stars. There is a wealth of information which can be utilized for science projects, for astronomy club activities, and for family learning.

As Co-Directors of HOA, John Percy and I gratefully acknowledge the funding provided to the AAVSO by the Education Division of the National Science Foundation (NSF) through Grant No. ESI-9154091, which enabled us to develop this curriculum. We express our sincere thanks to Dr. Gerhard L. Salinger, NSF Instructional Materials Development Program Director, who recognized the potential of our project and provided us with his invaluable guidance and recommendations throughout its development.

We express our gratitude to the thousands of amateur astronomers worldwide who contributed observations to the AAVSO International Database—without their efforts we would not have the real data on which the HOA curriculum is based.

Finally, we recognize with deepest appreciation the efforts of Donna L. Young, lead teacher and principal author of the HOA Manual, and the invaluable contributions of many teachers, students, amateur astronomers, AAVSO staff members, and other individuals to the development of *Hands-On Astrophysics*.

Janet Akyüz Mattei
AAVSO Director

Cambridge, Massachusetts, USA
December 1997

Foreword

In November of 1996, I attended the second *Hands-On Astrophysics* (HOA) teachers' workshop held at the Headquarters of the American Association of Variable Star Observers (AAVSO) in Cambridge, Massachusetts. At the time I was teaching astrophysics and AP physics at the Maine School of Science and Mathematics in Limestone, Maine (a new residential math and science magnet school for juniors and seniors). I was looking for that nonexistent middle-ground material for my astrophysics class—halfway between basic introductory astronomy content and calculus-intensive astrophysics. During that workshop, as I considered the preliminary HOA materials before me, I decided that the concept of variable star observation had the potential to be a truly innovative and exciting curriculum. I went back to the magnet school and introduced my students to the process of estimating magnitudes, plotting light curves, and constructing phase diagrams with the VSTAR software.

In northern Maine in the middle of winter, early evening temperatures are often -25 to-35°F. But the night sky is stunningly beautiful with frequent aurorae and myriad stars, and the winter cold did not deter my students. I literally could not stop some of them from making their nightly observations. Seeing their enthusiasm, the idea passed through my mind that I would like to develop some classroom materials for teachers based on what the AAVSO had begun.

A few months later I was granted a yearlong residential fellowship at the Wright Center for Innovative Science at Tufts University, directed by Eric Chaisson. At the same time, AAVSO Director Janet Mattei asked if I would be interested in working as a development consultant for the HOA curriculum, thereby contributing the perspective of a recognized master classroom teacher with extensive experience in state science initiatives and national workshops. I decided that my project for the year at the Wright Center would be *Hands-On Astrophysics*.

The more involved I became with HOA, the more excited I became over the potential that the curriculum held for so many students and teachers. For the past year and a half I have been extensively involved in rewriting some preexisting materials and making copious additions to the manual. I have made every attempt to ensure that the manual is as easy to use as possible for classroom teachers, and is as interesting as possible for students, amateur astronomers, and other individuals.

The HOA curriculum will not work for content-driven courses. Instead, it is a self-directed study, with minimal input from teachers, which involves students in real science. There is nothing artificial or arbitrary or contrived. *Hands-On Astrophysics* students will do science in exactly the same way that professional scientists do science every single day. There are no right or wrong answers: the process is everything. The content is assimilated along the way as necessary, not presented as long and tedious text. This curriculum empowers students to take charge of a learning process that is applicable to every facet of their lives, whether educational or personal. No other science is as interesting or fascinating as astronomy, and doing astronomy is more interesting and fascinating than reading about it. Students can gain incredible insight into the scientific process with nothing more than their eyes and the contents of this curriculum.

Hands-On Astrophysics is an invitation to embark upon a journey into the very hearts of stars—to listen to the rhythms of their pulsations, and begin to gain an understanding of the processes by which they evolve. Along the way, students will acquire the necessary skills and knowledge to determine and comprehend the message encoded within starlight, but the strength and power of the journey is that it involves a complete immersion into the scientific process—the very foundation of how we construct knowledge. Those who undertake this journey will also realize an added benefit: an appreciation of the stellar inhabitants of our universe that may result in a lifelong avocation as an amateur astronomer, with the potential of making significant contributions to science.

Finally, *Hands-On Astrophysics* takes students out of the artificial confines of classroom walls to gather observational data from the night sky above them. This is where they will begin their own individual journeys to the stars and feel the same deep stirrings that our ancestors felt when they looked towards the stars. We have not lost our fascination for the night sky. The colored and dancing display overhead causes us to pause and reflect, invoking deep longings that take us back through millennia and connect us to our past. Our origins are in the stars, and so is our future. When we look up we feel connected to the grandeur of the sparkling array above us. And that is the final powerful interdisciplinary aspect of this curriculum—that both people and stars are connected, occupying their own places in time and space, living and dying together in the same universe.

I am proud to have had the opportunity to help in the development of *Hands-On Astrophysics*. I hope it has a major impact on astronomy education worldwide.

Donna L. Young
HOA Manual Author
Curriculum Consultant

Medford, Massachusetts, USA
December 1997

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This chapter introduces the concept that processes that are periodic are predictable. For periodic variable stars, astronomers can use prediction to plan their observation of the stars, and also to look for deviations from periodicity. This chapter introduces the O-C diagram, which can determine deviations from predicted values.

CAUTIONARY SAFETY NOTE

1. Students should NEVER look directly at the Sun, especially when using binoculars or telescopes. The ultraviolet radiation from the Sun will damage the delicate cones and rods of the eye and can cause blindness. If students do not have specialized filters for solar observations provided or approved by their instructors, they should project the image of the Sun on the ground or a piece of paper.

2. Special precautions need to be taken for nighttime observations, whether at home or at school. Students should NEVER travel to or work alone in isolated areas. Make sure that the observational sites selected are safe, and always work with others. Inspect the chosen sites carefully, making note of any potential sources of danger such as construction areas, broken glass, etc. If working with power-driven telescopes outdoors, make sure that extension cords are properly grounded. If a site is located on private property, be sure to obtain permission (preferably written) from the owner ahead of time.

3. Parents or guardians of students should be informed of any assignments that students are required to do involving the observation of the sky, especially late at night. The proper school authorities should be notified, and permission slips signed by parents of younger students. Depending upon the age level of the students, one or more adults should accompany the group, such as parents, local astronomy groups, or amateur astronomers.

Using the Hands-On Astrophysics Manual

This manual addresses a wide range of grade levels (middle school through introductory college) and student abilities. It is flexible enough to meet the needs of the teachers and instructors of any of these grades. The following descriptions will tell you:

1. The conceptual framework around which the curriculum was built;
2. Information on each component within each chapter and the ancillary materials;
3. Several suggestions for presenting sequences of chapters and activities for specific student audiences.

The emphasis in this curriculum is on variable star observation, and so this manual is not intended to be a comprehensive astronomy textbook. There is, however, sufficient coverage here of most topics in elementary astronomy. ***You do not need any prior knowledge of astronomy or variable stars or physics to use this curriculum.***

1) Conceptual Framework

This curriculum supports the *National Standards for Science and Math Education* by directly involving students in the scientific process. Students are taught the necessary skills to make observations, analyze their data with graphing and statistical techniques, make predictions, and compare predicted and observational values, as well as learn how to develop sophisticated mathematical models. Except for a few exercises in skill development, there are no "right" answers in this curriculum. The data obtained, and the results of the analysis of those data by students, is the "right" answer. In variable star astronomy, what you see is what you get. The amount of data and the mathematical refinement techniques will give reasonably accurate results. Students will understand that their observations can be reliable, and that their data can be useful enough to be used by professional astronomers.

Each unit contains a paragraph, which describes the specific *National Science Standards* and *Benchmarks* themes, concepts, and content addressed in its chapters.

This is a curriculum on variable star observation; it is neither an astronomy course nor a statistics course. The information within the chapters has this purpose: to inform students about variable stars and their importance to the professional astronomical community, and to give them the necessary information and skills to study variable star behavior or to become amateur variable star observers. Therefore only the astronomy, math, and skills directly associated with variable stars are contained within these pages. However, interdisciplinary connections exist within the chapter introductions, Space Talks, and Poster Pages (explained below), and historical aspects of variable star astronomy have also been included. Thus parts of this manual can be used in any science computer, or math class, as well as in history and English classes. Besides being used as classroom material, the Hands-On Astrophysics (HOA) curriculum can be used for science fair projects, research projects in many disciplines, independent study, and enrichment activities.

Students will be able to access the American Association of Variable Star Observers (AAVSO) International Database, and share their investigations and observations with other students via the internet. Working together is an important aspect of the scientific enterprise, which is not usually understood within a traditional classroom setting. Sharing variable star observational activities with students in other geographical locations will enable data collection even when skies are cloudy.

One of the most powerful aspects of this curriculum is that it is intended to be interactive, both for students and instructors. Both will be able to access the AAVSO website and the Hands-On Astrophysics homepage. If you need answers to technical questions or assistance in locating data resources, you will be able to use the HOA website. Instructors can ask questions about any of the activities, or share their own activities with each other. You will be able to communicate with the authors of this curriculum and with professional astronomers and technicians.

If it is impossible for you to introduce your students to the night sky, the HOA curriculum is still of great value. Your students will be able to learn about variable stars by using the activities, software, and slide sets that come with the manual. So even if you are dealing with younger students or with city lights, the students can still study entire sequences of magnitude estimation, light curves, periodicity, phase diagrams, and prediction.

2) Chapter Components

THE MANUAL

There are two separate sections to this manual, one for teachers/instructors and one for students. The teacher pages give you suggestions for using the Activities, Poster Pages, and Investigations. These pages also contain suggestions for resources to enhance some of the activities. The student pages are set up so that Activities and Core Activities are on separate pages; in this way the instructors can easily photocopy only the activities they want to use. Except for the chapter entitled “The Nature of Light,” all materials required for the activities are either in this manual, or are easily and inexpensively attainable. **Teachers should read the student pages before reading the teacher pages.**

Misconceptions: Students typically have many misconceptions about astronomy and physical science. We have listed only the specific misconceptions, which are directly addressed within the activities of a particular chapter. Some chapters do not address any misconceptions—therefore none are listed.

Investigations: Most chapters have Investigations, and none of these have specific answers. Their purpose is to have students begin thinking about concepts which may be new to them, or about which they may have misconceptions. Investigations are meant to be a discovery process; the object is to have students think about and discuss the concept being presented.

Core Activities: The Core Activities are those that are necessary for acquiring skills and/or for understanding key concepts. However, if you have students who are already familiar with the material within some of the Core Activities, then you can leave that material out. For example, middle school students probably have not learned about the Kelvin temperature scale. They should, however, understand the basis of the scale, since it is used in stellar astronomy. If your students have had chemistry, they already have used this scale. Or, you may use the temperature conversion activity as a review classroom activity only. Perhaps some of your students have either had chemistry or physics, or learned the Kelvin scale in another class, and other students have not. Then only the students who need to learn about the Kelvin scale should do the temperature conversion activity.

Activities: Some activities are included which are not really necessary for understanding basic concepts or acquiring a necessary skill. Some are further treatments of concepts not easily acquired, and some are merely interesting related topics, such as the sky pollution activity.

Space Talks: The Space Talks address topics which give general information not included within the chapter activities or introductions. They cover a wide range of topics that are related in direct or indirect ways to the chapter content, except for Unit 5, which deals with mathematical analysis. Therefore the Space Talks in that unit are about more technical topics such as eclipsing binary star systems.

Terminology: The vocabulary words on the teacher pages are not necessarily the words that are the focus of the chapter; sometimes none of them are. The vocabulary words are the words that are either in bold type in the Space Talks or in italics within the student chapters. Sometimes the Space Talks contain words which are relevant to the activities within the chapter, or sometimes they involve extensions. All of the vocabulary words are defined in the glossary; a listing by chapter is also given in the Appendix.

Poster Pages: These pages can be utilized in several ways. They present important or interesting aspects of related topics, and are usually historical in nature. From Polynesian celestial navigation to Abraham Lincoln and the Almanac Trial, these pages contain i**n**terdisciplinary connections with stellar astronomy and celestial phenomena. The back of each Poster Page relates to the material given on the front. A substantial amount of this material asks a series of questions which can be used for classroom discussion, research topics for history and/or English classes, term papers, and classroom oral presentations. In the teacher pages, further information on the Poster Page topic is also given. The Poster

Pages are related to the chapters in which they are located, but can be used in any order and at any time, and can be posted on the board as either an introduction or conclusion to a chapter.

Resources: We have listed some suggestions for added reinforcement where appropriate. These are noted by a RESOURCE flag in the margin. The addresses, phone numbers, and other pertinent information for obtaining these items can be found in the Resource List in the appendix.

Appendix: This section includes the HOA web site information, a guide to observing eclipsing binary stars, a summary of variable star types, a list of HOA stars, the VSTAR, HOAENTER, and HOAFUN software documentation, the resource list, a reference list for further reading, and a two-part glossary. The glossary contains the bold-type terminology in the Space Talks and any italicized terms occurring in a chapter. Any other terminology is explained within the student chapters. Your students do not need to memorize these terms. The Space Talks are informational only and are not necessary for the activities.

Ancillary Materials

HOAFUN, HOAENTER, and VSTAR: HOAFUN is a software program which introduces students to magnitude estimation and light curves. It is simple, non-threatening, and easy to understand, even for younger students. It is a good introduction to how variable stars produce light curves which can be analyzed for periodicity.

HOAENTER is a data-entry program which may be used to prepare data for loading into the VSTAR program or to prepare data to submit variable star observations to the AAVSO.

VSTAR is a dual-purpose software: 1) It will display a graph of the several dozen stars from the included AAVSO International Database, or from data provided by the students themselves; and 2) It is a sophisticated, powerful mathematical and statistical data analysis tool. Both teachers and students can use the VSTAR program to look at different types of variable stars, their light curves, and determine their periods, as well as analyze the periodicity by producing phase diagrams. A complete VSTAR manual is included in the appendix.

HOA Video: The video consists of four segments. The first is a four-minute introduction featuring teachers who have used this curriculum with their students. They discuss the valuable ways that variable star observation has helped their students acquire appreciation for and knowledge of the scientific enterprise. The video's three main segments are approximately 20 minutes each. They are entitled *Backyard Astronomy, Variable Stars,* and *How to Observe Variable Stars.*

Backyard Astronomy introduces the idea that you can observe and learn a great deal about the universe from your own backyard. *Variable Stars* gives a brief introduction to the nature of variable stars. *How to Observe Variable Stars* shows the process involved in observing, data collecting, and analysis of variable stars. These videos can be shown in any sequence and at any time during the course of the curriculum. Two real high school students are prominently featured in the video. One has extensive experience observing variable stars, and the other is an interested amateur just starting to learn about variable stars.

Slides and Prints: There are a total of 31 slides. Of these, there are 18 constellation slides [2 for Auriga (Aur), 7 for Cygnus (Cyg), 1 for Ursa Major (UMa), 6 for Cepheus (Cep), and 2 for Cassiopeia (Cas)], as well as 7 slides for the variable star W Cyg. In addition, there are 6 finder slides, 1 for each constellation and 1 for W Cyg. Also included are photographic prints for each of the 7 Cyg constellation slides and the 7 W Cyg slides, for a total of 14 prints. The activities that go with these prints and slides give several suggestions as to how they can be used.

Charts: There are a total of 45 charts. Included are: a) 5 large-scale constellation finder charts to help locate the HOA constellations and the general location of variable stars; and b) a series of 11 a-scale, 2 aa-scale, 11 b-scale, 5 c-scale, 9 d-scale, 2 e-scale and 5 constellation charts which show the locations of the following 15 variable stars and give the locations and magnitudes of their comparison stars: R Aur, RT Aur, chi Cyg, W Cyg, X Cyg, U Cyg, R UMa, S UMa, Z UMa, T Cep, S Cep, delta Cep, U Cep, R Cas, and V Cas.

3) POSSIBLE SEQUENCES

The material within this curriculum is laid out in sequence, from easiest to most difficult. However, using the complete sequence is only one of many options available. If you have a full or half-year astronomy course at the middle or high school level you may use this option. If you have students with some science and math background at the college or high school level, you may want to leave out the first two units and start with Unit 3. Even though the sequence presented has a specific direction and relationship, the units or chapters can also be used independently. ***The chapters are related to each other, but do not depend upon one another.*** Even though you may not have an astronomy, physical science, or math class in which to use this curriculum, you may decide to select certain parts of it to include within an English, history, or biology class. A few of the many options are as follows:

If your interest is solely in variable star observations and data analysis, or you have college or high school students:

1. Core Activity 6.5: Collecting Your Own Data
2. Chapter 7: Observing Variable Stars in the Sky
3. Unit 5: Analysis of Variable Stars

    Chapter 10: Statistical Concepts

Chapter 11: Variable Stars, Light Curves, and Periodicity

Chapter 12: Variable Stars and Phase Diagrams

Chapter 13: Variable Stars and O-C Diagrams

If you have middle school students:

1. Unit 1: Planets and Stars

    Chapter 1: The Solar System and Beyond

    Chapter 2: The Nature of Stars

2. Unit 2: Introducing the Sky

    Chapter 3: Familiarizing Yourself with the Night Sky

3. Unit 3: Observing Variable Stars

    Chapter 5: Introducing the Hands-On Astrophysics Constellations

    Chapter 6: Measuring Variable Stars Visually

    Chapter 7: Observing Variable Stars in the Real Sky
    (OMIT if your students are unable to observe at night)

4. Unit 5: Analysis of Variable Stars

    Chapter 10: Statistical Concepts

    Chapter 11: Variable Stars, Light Curves, and Periodicity

If you have a computer or statistics class:

1. Core Activity 6.5: Collecting Your Own Data

2. Unit 5: Analysis of Variable Stars

    Chapter 10: Statistical Concepts

    Chapter 11: Variable Stars, Light Curves, and Periodicity

    Chapter 12: Variable Stars and Phase Diagrams

    Chapter 13: Variable Stars and *O–C* Diagrams

If you have a physics or physical science class:

1. Unit 4: The Message of Light

    Chapter 8: The Nature of Light

    Chapter 9: The Life of a Star

4) HOA WEBSITE

There is a schematic of the *Hands-On Astrophysics* Website in the Appendix. The website is accessible through the AAVSO website *(http://www.aavso.org)*, and includes the following sections:

1. About *Hands-On Astrophysics*

This section gives information about variable stars, and background information about the American Association of Variable Star Observers (AAVSO). A brief history of the HOA project, the AAVSO's International Database on variable stars, who accesses the database and why are all explained here, along with an introduction to AAVSO director Janet Mattei, the AAVSO technical staff, and project co-director John Percy. HOA newsletters will be included as well as links to other astronomical and science education websites.

2. *Hands-On Astrophysics* Materials

This section introduces and provides samples of the HOA curriculum and ancillary materials, including the Manual and its table of contents, the AAVSO International Database, star charts, slides and prints, HOA videos, and other resources which would be useful in using the *Hands-On Astrophysics* materials.

3. Talk To Us!

This section has the HOA e-mail interface, a direct link to the HOA webmaster (an experienced teacher) for teachers and students who have questions or ideas, or who need assistance with projects, etc. An evaluation form is located here so teachers may evaluate any part of the materials being used. Students also may wish to comment on the use of the manual and other materials. Feedback will be posted, so if you find better methods of completing some of the activities, or would like to see a particular activity included, or a poster page developed on a specific topic, this is the place!

4. *Hands-On Astrophysics* Activities

This section includes sample investigations, activities, and poster pages from the manual, along with previously-developed HOA observing activities. The samples will be representative of the entire manual and available for downloading.

5. What's New with *Hands-On Astrophysics*

This section includes news updates about HOA and/or the AAVSO, as well as new HOA materials, including ideas culled from the HOA e-mail link. Relevant news items about variable star research, and results of student projects will also be posted. For teachers, notices about upcoming workshops, conferences, presentations, etc., will be posted here, as well as reports on past workshop activities.

6. Order Forms

Information and order forms will be available for the *Hands-On Astrophysics* materials, AAVSO publications, AAVSO star charts, AAVSO membership, and the *Hands-On Astrophysics* and AAVSO stellar gifts (T-shirts, sweatshirts, mugs, keychains with red light, hats, etc.). There will also be links to other astronomical gift websites.

SUMMARY

- ✓ The *Hands-On Astrophysics* (HOA) curriculum can be a complete course of study, or you can use individual chapters or any combination of chapters.
- ✓ The content is useful in astronomy, physical science, mathematics, and computer classes, and has interdisciplinary connections that make it appropriate for history or English classes, or public education programs.
- ✓ The material is appropriate for middle school through introductory college level, depending upon the chapters selected.
- ✓ The curriculum is self-contained: no prior knowledge of astronomy, variable star astronomy, or physics is necessary.
- ✓ HOA actively involves students in the scientific process through observation, data collection, graphical and computer analysis, mathematical models, prediction, and assessment of prediction and further observation.
- ✓ HOA participants can access the AAVSO International Database and talk directly with others engaged in variable star observing. They can also communicate with the AAVSO headquarters staff via the AAVSO website.

Chapter 1: The Solar System and Beyond

"Insignificance", artist Lola Chaisson

Introduction

Going out at night to look at the bejeweled and mysterious sky is not something we usually do. People of ancient and prehistoric times turned their eyes to the sky every night because the motions of the Sun, Moon, stars and planets served as their calendar, clock, and compass. The sky told them when to plant and harvest their crops, when the game herds would migrate, and the direction in which to travel. Knowledge of the sky was not only necessary for survival—the sky was also worshipped as the home of the gods. Viewed in this way, the sky gave people mixed feelings of awe, insignificance, and peacefulness. Ever since the first stirrings of consciousness, humankind has lifted its eyes towards the mystery of the heavens and found solace in the contemplation of celestial objects. The heavens seemed so calm and eternal and comforting.

However, the quietude of the universe is an illusion. The stars in the sky are not eternal; they are born from nuclear fires, they live, and ultimately die. Some stars die quietly, some literally tear themselves apart with violent explosions, and still others leave the visible universe when they die to become the most exotic objects in the known universe—black holes.

Beyond the stars in our Milky Way Galaxy are other galaxies—and sometimes one of these galaxies, containing billions of stars, will collide with and consume another galaxy like a cosmic cannibal. Comets and asteroids restlessly roam through space, sometimes crashing into planets and moons with catastrophic results.

The night sky seems so peaceful, yet masks a maelstrom of activity that we are not easily able to detect with our eyes alone. How can we, when we cannot even detect our own motions? The Earth is spinning around at up to 1670 km/hr, depending on latitude, and orbiting around the Sun at 30 km/s; the Sun is orbiting the center of the Milky Way Galaxy at 250 km/s, and the Milky Way Galaxy itself is moving through spacetime. The Sun and Solar System travel 971,000,000 km every year in their orbit around the galactic center. (How many galactic miles have you traveled so far in your lifetime?) We are on a roller coaster ride of universal proportions, and we feel nothing. How very strange is this world we inhabit!

Chandra X-Ray Observatory
http://chandra.harvard.edu/

The rate at which we receive new information and expand our knowledge in astronomy has increased phenomenally. This is due in part to sophisticated technology such as the earthbound Keck Telescope on a mountain top in Hawaii, the Hubble Space Telescope orbiting the Earth, and the Chandra X-Ray Observatory in an extreme orbit that reaches more than one third of the distance to the Moon. When we see the constant stream of beautiful images from these instruments, it is easy to forget that humankind gained an incredible depth of understanding of our local universe by *visual* observation with the aid of a few *simple* astronomical tools. Making observations over periods of time, recording data, and developing predictions from the analysis of the data, is *still* how science works, no matter how glitzy or high-tech, or even how simple, the tools we use are.

You have the ability to travel to the far reaches of space. You can make a journey through your eyes and mind that would otherwise be physically impossible due to the immense distances involved. Traveling at 968 km/hr by 747 jet, it would take 17 years to reach the Sun, and an amazing 4,600,000 years to reach just the nearest star! We cannot travel to the stars, but we can still come to know them well by reading the messages they sent out a very long time ago.

So let the stars get in your eyes and become initiated into the wonders of the universe from your own backyard. Your life will be enriched with a newfound knowledge as you learn how to read the messages encoded within the starlight traveling through spacetime and falling into your eye. You will be able to use this information to understand the unstable and violent nature of seemingly peaceful and stable stars. So look up! Watch the stars! Get to know the stars and constellations, make a quadrant, learn how to use a planisphere, and begin to enjoy the pleasures of the cosmos!

Who is more important?

Tycho Brahe

Tycho Brahe (1546–1601, shown at left) was a nobleman from Denmark who made astronomy his life's work because he was so impressed when, as a boy, he saw an eclipse of the Sun take place at exactly the time it was predicted. Tycho's life's work in astronomy consisted of measuring the positions of the stars, planets, Moon, and Sun, every night and day possible, and carefully recording these measurements, year after year.

Johannes Kepler (1571–1630, below right) came from a poor German family. He did not have it easy growing up. His father was a soldier who was killed in a war, and his mother (who was once accused of witchcraft) did not treat him well. Kepler was taken out of school when he was a boy so that he could make money for the family by working as a waiter in an inn. As a young man Kepler studied theology and science, and discovered that he liked science better. He became an accomplished mathematician and a persistent and determined calculator. His essentially religious mind drove him to find an explanation for order in the universe. He was convinced that the order of the planets and their movement through the sky could be explained through mathematical calculation and careful thinking.

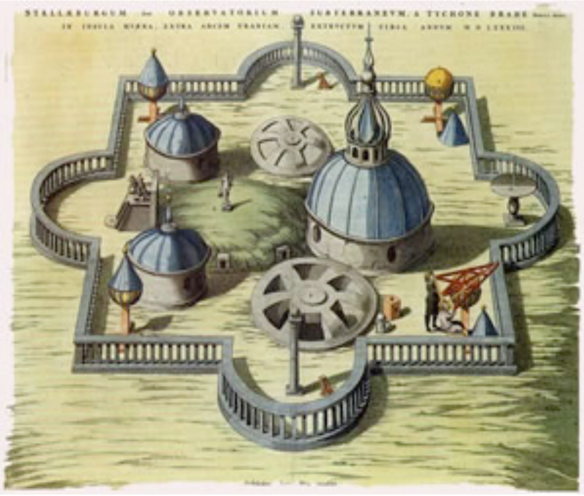
Johannes Kepler

Tycho wanted to study science so that he could be one of those people who could predict eclipses. He studied mathematics and astronomy in Germany. Then, in 1571, when he was 25, Tycho built his own observatory on an island (the King of Denmark gave him the island and some additional money just for that purpose). Tycho named his island observatory Uraniburg-Urania being the muse of astronomy. He lived and worked in his observatory for 20 years with many astronomers and assistants. Tycho's main goal was to determine the positions of the stars and planets as accurately as possible. This could only be done by constructing precision observing instruments and by making and recording many observations of stars and planets night after night.

Kepler became interested in science and mathematics when in school at about the age of 18. He was not particularly interested in astronomy until 1600 when Kepler met Tycho Brahe in Prague, and Tycho asked him to be his assistant. Tycho would pay him well. But Tycho died one year later, and even though Kepler was appointed astronomer to the court, he found so little official support for his position that he had to survive by making astrological predictions for noblemen who wanted their fortunes told.

Tycho was a scientist who worked by direct observation. Kepler was a scientist who worked by calculation and testing one idea after another. Tycho's life's work of measuring the positions of objects in the sky was in itself useless without someone like Kepler to come along and make sense of those measurements. In the same way, Kepler's efforts to understand how the planets moved would be nothing but speculation, guessing, and mysticism if he did not have the basic data, the accurate measurements made by Tycho, against which to test his ideas and theories. Each one's work is meaningful because of the other's work.

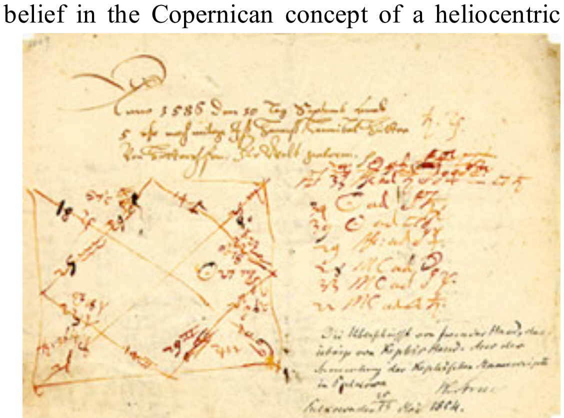
The scientific contributions of these two astronomers from radically different backgrounds are set against a time of great turmoil in European history-the early 1600's. It was a time of upheaval, superstition, and fear-a time when court astrologers were powerful, and the stars were thought to predict and guide one's destiny.



Tycho Observatory on the Island of Ven

Tycho Brahe was a Danish nobleman and held the position of Royal Mathematician at the court-in-exile of the Holy Roman Emperor, Rudolf II, in Prague (in the former Czechoslovakia). He was arrogant, conceited, and obnoxious. While at university he had a duel with a fellow student over which one was the best mathematician. Tycho may have been the superior mathematician, but he was not the better duelist: during the encounter he lost his nose, which he replaced with one made of gold. He had different metal noses which he changed depending upon the occasion (the recent exhumation of his body proved that he did indeed sport a metal nose). At a dinner given by a local Baron, Tycho consumed great quantities of wine but would not leave the table in the presence of the Baron, considering it to be rude behavior. The resulting urinary tract infection, along with Tycho's refusal to stop abusing his body with overdrinking and overeating, led to his death a few months later.

Johannes Kepler was born into much humbler surroundings. He expected to enter the clergy, but instead became a mathematics teacher in Graz, Austria. His belief in the Copernican concept of a heliocentric universe was a dangerous one. With the coming of the 30 Years' War, Kepler and his wife were exiled due to their Protestant beliefs. During his time in Prague, he fought continually with Tycho, who refused to share his meticulous observations with him. These were observations which Kepler desperately needed for his continuing quest to establish the true orbital motions of the planets.



Kepler manuscript

After Tycho's death, Kepler stole the data. Eventually the war reached Prague, and Kepler was once again persecuted for his religious beliefs. He also lost his wife and son to a plague, and his mother was convicted of witchcraft and imprisoned. Eventually, however, Kepler was able to have her death sentence commuted to one of exile. During this time Kepler wrote one of the first science fiction stories, entitled "Somnium," or "The Dream." This story probably contributed to his mother's persecution as she resembled one of the characters, an old woman who had dealings with demons and devils. Kepler finished his days in poverty, writing horoscopes for noblemen in order to survive.

Tycho Brahe and Johannes Kepler had totally disparate backgrounds and temperaments. In spite of this, Tycho's painstaking and detailed observational data, combined with Kepler's mathematical genius, allowed Kepler to derive the following three laws of planetary motion:

1. The planets move in an ellipse with the Sun at one focus.

2. The orbit of a planet sweeps through equal areas in equal times (see diagram just above Kepler's picture on other side).

3. The square of the period in years is equal to the cube of the mean distance (with the unit of measurement in Astronomical Units [AU]).

Investigation 1.1: Sizes and Distances of the Sun, Earth, Moon, and Planets

Models can be extremely useful in helping us understand relationships, but they can also be misleading. To use models effectively, it is important to understand how a model may be different from what it represents. To begin your investigation of the sizes and distances of the objects in the Solar System, your instructor will give you some materials to work with and some activities to do. Later on, you will construct your own scale models of the Sun and planets.

You are familiar with models—they exist everywhere. We make models to help us "see" things that are too large for us to see—such as the Solar System and the Milky Way Galaxy—and things that are too small, such as the structure of an atom or a bacterium. Models can also help us to understand what happens when the time it takes for things to happen is very long—the movements of the continents caused by plate tectonics, for example. Models can take many forms. Some are physical models, such as maps and globes. Others are mental models, such as the "Bohr" model of the atom that comes to mind when we think of atoms. Still other models are mathematical, such as the equations that model the curvature of spacetime, which is impossible to make into a physical model, or even into a mental image.

All of these models have distortions. Flat maps of the Earth get more exaggerated towards the edges—putting a round shape onto a flat surface causes some of the countries to look larger than they really are. However, they are still useful because they help us see relationships and because they are convenient. A flat map may be folded up and put in your pocket. So there are trade-offs between accuracy and convenience whenever you construct a model.

Portraying the Solar System is also difficult to do with complete accuracy. All pictures and models are inaccurate. We are so used to seeing pictures that are not drawn to scale that we have no sense of distances or sizes in relation to ourselves. And if we cannot even feel how far 150,000,000 kilometers is (the distance from Earth to the Sun), how can we even begin to imagine the enormous distances to the stars and other galaxies?

We are misled by every representation of the Solar System that we see, yet we would be unable to understand the structure of our planetary family without these same models. So as you begin your exploration of sizes and distances and construct your own models, remember that not only is it important to develop a model to show some aspect of the Solar System, it is also important to understand what aspects of your model are not correct.

Your instructor will now provide you with the materials necessary for you to begin your investigation of the sizes and distances within the Solar System.

Core Activity 1.2: Unit Conversion

You will be constructing scaled-down models, which always require conversion from large-scale measurements to smaller ones. There is a simple but powerful method which can be applied to any type of unit conversion you need to calculate. Units are **always** included with the numerical value in scientific calculations. Consider the following examples:

EXAMPLE 1:

How many seconds are there in one year? You already know all of the parts you need to easily calculate the answer:

1. There are 60 seconds in a minute;
2. 60 minutes in an hour;
3. 24 hours in a day;
4. 365.24 days in a year.

There are two things you need to know; ***identical units cancel*** each other in the same way that identical numbers do. If you have:

$$\cancel{3} \times \frac{2}{\cancel{3}}$$

you can cancel the 3's and know the answer is 2 without multiplying and dividing. The same method applies to units. Also, two values can be equal to each other even if the units are different. Since 60 minutes is the same amount of time as one hour, then 60 minutes divided by one hour (which is a fraction) is equal to one. Let's now calculate how many seconds there are in a year. We want all units except seconds and year to cancel.

$$\frac{60 \text{ seconds}}{1 \cancel{\text{ minute}}} \times \frac{60 \cancel{\text{ minutes}}}{1 \cancel{\text{ hour}}} \times \frac{24 \cancel{\text{ hours}}}{1 \cancel{\text{ day}}} \times \frac{365.24 \cancel{\text{ days}}}{1 \text{ year}} = 31{,}556{,}736 \text{ seconds/year}$$

Maybe you already know there are 3600 seconds in an hour (by looking at the number in the conversion table provided following Example 5). Then the conversion will be shorter:

$$\frac{3600 \text{ seconds}}{1 \cancel{\text{ hour}}} \times \frac{24 \cancel{\text{ hours}}}{1 \cancel{\text{ day}}} \times \frac{365.24 \cancel{\text{ days}}}{1 \text{ year}} = 31{,}556{,}736 \text{ seconds/year}$$

EXAMPLE 2:

You throw a baseball at 85 miles/hour and want to know how many inches the ball is traveling each second; that is, you want to convert miles/hour to inches/second. We will start with miles/hour and keep going until all units have cancelled out except for inches in the numerator and seconds in the denominator.

This is a two-part problem. First we will convert miles into inches. Then we will convert hours into seconds.

1. Miles into inches:

   From the conversion table you find the following information:

   1 mile = 5280 feet; 1 foot = 12 inches

   $$\frac{85\ \cancel{\text{miles}}}{\text{hour}} \times \frac{5280\ \cancel{\text{feet}}}{1\ \cancel{\text{mile}}} \times \frac{12\ \text{inches}}{1\ \cancel{\text{foot}}}$$

2. Hours into seconds:

   We have now converted the miles into inches. Now we need to convert the hours into seconds by extending from what we have already converted.

   $$\frac{85\ \cancel{\text{miles}}}{\text{hour}} \times \frac{5280\ \cancel{\text{feet}}}{1\ \cancel{\text{mile}}} \times \frac{12\ \text{inches}}{1\ \cancel{\text{foot}}} \times \frac{1\ \cancel{\text{hour}}}{3600\ \text{s}} = \frac{5{,}385{,}600\ \text{inches}}{3600\ \text{seconds}}$$

   = 31,556,736 inches/year

   In other words, once all the units have cancelled except the ones you want, multiply all numbers in the numerator, all the numbers in the denominator, and divide the numerator by the denominator to calculate your answer.

   $$\frac{85 \times 5280 \times 12}{3600} = \frac{5{,}385{,}600}{3600} = 1496\ \text{inches/second}$$

Example 3:

1. 150 kilometers(km)/hour is how many miles/hour?
2. From the table, 1 km = 1000 meters (m); 1609 meters (m) = 1 mile;
3.

$$\frac{150\ \cancel{km}}{hour} \times \frac{1000\ \cancel{m}}{1\ \cancel{km}} \times \frac{1\ mile}{1690\ \cancel{m}} = \frac{150{,}000}{1609} = 93\ miles/hour$$

Example 4:

1. 150 km/hour is equal to how many meters/second?
2.

$$\frac{150\ \cancel{km}}{\cancel{hour}} \times \frac{1000\ m}{1\ \cancel{km}} \times \frac{1\ \cancel{hour}}{3600\ seconds} = \frac{150{,}000}{3600} = 41.7\ meters/second$$

Example 5:

1. 5000 kilometers is how many miles?
2.

$$5000\ \cancel{km} \times \frac{0.62\ miles}{1\ \cancel{km}} = 3100\ miles$$

Conversion Table

1. 1 kilometer (km) = 1000 meters (m) = .62 mile (mi)
2. 100 centimeters (cm) = 1 meter
3. 1 mile = 5280 feet (ft) = 1609 meters
4. 1 inch = 2.54 centimeters
5. 1 hour = 3600 seconds (s)

Practice Problems for Unit Conversion:

1. Recalculate Example 3 above, using a different (and shorter) conversion.

2. 3,000 miles is how many kilometers?

3. 3,655,000 centimeters is how many miles?

4. 7 miles/second is how many
    a. miles/hour?

    b. kilometers/hour?

    c. feet/hour?

    d. meters/hour?

5. How many hours are there in 35 years?

6. Calculate a rough estimate of how many hours of your life you have spent sleeping.

Core Activity 1.3: String Model of the Solar System

You are going to build your own scale model of planetary distances in the Solar System. The longest distance you can use will determine the scale of the model.

Longest Usable Distance (meters)	Distance to Pluto (AU)	Scaling Factor (m/AU)
	39.4	

1. Measure this distance to the nearest meter and record it in Table 1.1a. This number represents the distance between the Sun and Pluto (39.4 AU or $5.9x10^9$ km.) You will begin using a unit that may be unfamiliar, the *Astronomical Unit* (AU). The distance from Earth to the Sun is about 150 million kilometers, which is assigned the value of 1 AU.

2. To calculate the distance from the Sun to the planets, you need to determine the scaling factor. Divide the largest usable distance by the distance to Pluto in AU's. This is the scaling factor. Your scaling factor is ______ m/AU. Enter this number into Table 1.1a.

TABLE 1.1b

Planet/Star	Distance from the Sun (AU)	Scale Distance from Sun (meters)	Actual Average Distance(kilometers)	Actual Diameter (kilometers)
Sun				1,391,980
Mercury	0.39		58,000,000	4,880
Venus	0.72		108,000,000	12,100
Earth	1.00		150,000,000	12,800
Mars	1.52		228,000,000	6,800
Jupiter	5.20		778,000,000	142,000
Saturn	9.54		1,430,000,000	120,000
Uranus	19.2		2,870,000,000	51,800
Neptune	30.1		4,500,000,000	49,500
Pluto	39.4		5,900,000,000	2,300

3. Multiply the scaling factor by the distance from the Sun to each of the planets in AU's, and record in the column labeled "Scale Distance from Sun" in Table 1.1b.

4. Measure out a length of string equal to the scaled distance from the Sun to Pluto. Mark the points along the string where the planets are located and attach a flag or marker at these points.

Questions:

1. Does your model resemble the mental picture you had of the spacing between the planets? If not, how does it differ?

2. If different scale models have been produced, are some inaccurate? Can they all be "correct"? If so, then are some more "useful" than others? Why or why not?

3. Is it possible to have the same scale model for the sizes of the planets? Why or why not?

4. What are some of the inaccuracies of your scale model? If there are "wrong" aspects to your model, is it still useful?

5. The nearest star to Earth is Proxima Centauri, 266,000 AU away. Where would this star be placed in your scale model of the Solar System?

1 kilometer (km) = 1000 meters (m) (10^3) 1 centimeter (cm) = 1/100 meter (m) (10^{-2}) 1 millimeter (mm) = 1/1000 meter (m) (10^{-3})

Core Activity 1.4: Mathematical Estimation of Sizes and Distances

1. If the Sun is represented by the dot shown in the right corner of the box above, what is your best estimate for the size of the Earth and its distance from the Sun? Draw the Earth to scale and place it on the page at your estimated location.

    a. The average distance from the Earth to the Sun is about 15×10^7 km (150 million km), and the approximate diameter of the Sun is 14×10^5 km (1 million, 400 thousand km). How many solar diameters is the Earth from the Sun?— that is, how many Suns can fit between the Earth and the Sun?

    b. The circle representing the Sun has a diameter of 2 millimeters (mm). How far away is the Earth from this scale model Sun? Measure the distance and mark the location. Does it agree with your estimation?

    c. The diameter of the Earth is 13×10^3 km (13,000 km). The Sun's diameter is how much larger than that of the Earth?—that is, how many Earths would fit across the diameter of Sun's disk?

    d. What would be the Earth's diameter if it was on the same scale as the circle above? Does this agree with your estimation? Can you draw this diameter on this page?

2. For a different scale model, the Sun is represented by a soccer ball having a diameter of 25 cm.

    a. How far from the Sun is the Earth in centimeters? In meters?

    b. What is the Earth's diameter using this scale?

    c. The farthest planet from the Sun, Pluto, is 40 times farther away from the Sun than the Earth. How far from the Sun is Pluto in the soccer ball Solar System?

    d. What would be the diameter of the entire Solar System on this scale?

    e. Calculate the diameter of the star Betelgeuse (actual diameter of 420×10^6 km, or 420 million kilometers) on this same scale.

f. Proxima Centauri, the star closest to the Sun, is 266,000 times farther from the Sun than the Earth in this model and has the same diameter as our Sun. How far away is Proxima Centauri?

g. If the soccer ball Sun is placed in your house, determine the geographical location where Proxima Centauri would be found.

3. Create your own scale model by setting the size of the Earth to be that of any object you choose. Using the size of your object, calculate the scale values for the objects in the following table.

The diameter of your object is ______.

TABLE 1.2a

Star or Planet	Scale Diameter (meters)	Scale Distance (meters)	Scale Distance (km)
Sun			
Moon*			
Jupiter			
any other planet (see chart below)			
Proxima Centauri			
Betelgeuse**			

* The moon is 1/4th the diameter of the Earth and is ~38 x 10^4 km away.
** Distance from Sun to Betelgeuse is ~4.1 x 10^{15} km

TABLE 1.2b

Planet	radius (km)
Mercury	2,440
Venus	6,052
Earth	6,378
Mars	3,397
Jupiter	71,492
Saturn	60,268
Uranus	25,559
Neptune	24,764
Pluto	1,151

An Arm's-Length Reach into the Universe

In 1977 NASA launched the twin spacecraft Voyager 1 and Voyager 2. The Voyagers explored the giant outer planets of our Solar System, their moons, and the systems of rings and magnetic fields of those planets. These two spacecraft are now beyond the orbit of Pluto and heading for interstellar space.

Voyager - http://voyager.jpl.nasa.gov/

Voyager 1 encountered Jupiter in 1979, and Saturn in 1980. Voyager 2 encountered Jupiter in 1979, Saturn in 1981, Uranus in 1986, and Neptune in 1989.

Voyager 1 is now leaving the Solar System, rising above the ecliptic plane at an angle of about 35 degrees at a rate of about 520 million kilometers (about 320 million miles) each year.Voyager 2 is also headed out of the Solar System, diving below the ecliptic plane at an angle of about 48 degrees and a rate of about 470 million kilometers (about 290 million miles) a year.

Eventually, Voyager 1's instruments may be the first of any spacecraft to sense the heliopause-the boundary between the end of the Sun's magnetic influence and the beginning of interstellar space.

The heliopause is the outermost boundary of the solar wind, where the interstellar medium restricts the outward flow of the solar wind and confines it within a magnetic bubble called the heliosphere. Exactly where the heliopause is has been one of the great unanswered questions in space physics. By studying radio emissions, scientists now theorize the heliopause exists some 90 to 120 astronomical units (AU) from the Sun.

The Solar System does not end at the orbit of Pluto, the ninth planet. Nor does it end at the heliopause boundary, where the solar wind can no longer continue to expand outward against the interstellar wind. It extends over a thousand times farther out where a swarm of small cometary nuclei, known as the Oort Cloud, is barely held in orbit by the Sun's gravity.

But even at speeds of over 35,000 mph, it will take nearly 20,000 years for the Voyagers to reach the middle of the comet swarm, and possibly twice this long for them to pass the outer boundaries of cometary space. By then, they will have traveled a distance of two lightyears, equivalent to half of the distance to Proxima Centauri, the nearest star.

Once the Voyager spacecraft leave the Solar System (by 1990, both were beyond the orbit of Pluto), they will find themselves in empty space. What can they do out there then? For the next 20 to 30 years, the Voyagers will continue to send information about ultraviolet light from the stars, and data about magnetic fields, radio emissions, cosmic rays, and charged particles in space.

The Voyager spacecraft will be the third and fourth human artifacts to escape entirely from the Solar System (the first two were Pioneer 10 and 11, launched in 1973 and 1974).

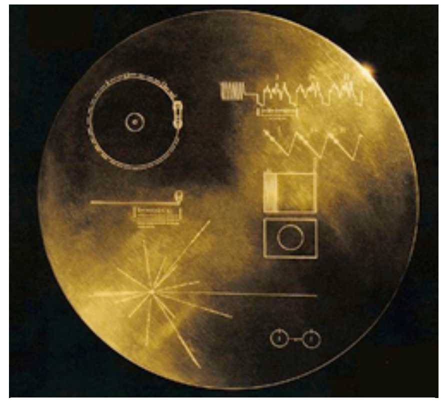
Plaques identifying the time and place of origin were mounted on the Pioneer spacecraft, should any other spacefarers find them in the future.

Think of it: it took about 13 years for the Voyagers to reach the orbit of Pluto, but it will be 40,000 years before they make a close approach to any other possible planetary system.

The message affixed to the Voyagers is much more elaborate: in addition to information about the spacecrafts' origin, there is a 12-inch gold-plated copper disk containing sounds and images selected to portray the diversity of life and culture on Earth. Among these are sounds of surf, wind, birds, and whales; music from many cultures and eras, from ethnic, to classical, to rock-and-roll; and spoken greetings from Earth-people in 55 languages.

As astronomer Carl Sagan pointed out, the spacecraft will be encountered only if there are advanced spacefaring civilizations in interstellar space. But the launching of this bottle into the cosmic ocean says something very hopeful about life on this planet.

(Adapted from NASA information files.)



Message aboard Voyager

What is the probability that life other than our own exists in the universe? How many galaxies, how many stars, how many civilizations? The Drake equation is an attempt to estimate how many others, similar to ourselves in technological advancement, there may be in just one galaxy-the Milky Way:

$N = (N^*) (f_p) (n_e) (f_l) (f_i) (f_c) (f_L)$

where

1. N^* is the number of stars in the Milky Way Galaxy;
2. f_p is the fraction of stars that have planetary systems;
3. n_e is the number of planets in a system ecologically suited for life;
4. f_l is the fraction of suitable planets on which life actually evolves;
5. f_i is the fraction of inhabited planets on which intelligent life evolves;
6. f_c is the fraction of planets on which advanced technology develops;
7. f_L, is the fraction of a planetary lifetime inhabited by a technical society.

This equation involves physics, chemistry, biology and earth science. It attempts to quantify complex factors. Is the equation adequate? How would you derive the best estimates for the quantities within the equation? How many civilizations do you get?

What would you have sent on Voyager to try and summarize millions of years of human evolution on planet Earth? How do you explain the human condition to alien eyes and ears? What music? What sounds? What artifacts? Music is an expression of the human spirit. Is it important to other life forms? Will it reveal more or less about us than the mathematics of prime numbers and the cryptic lines and diagrams engraved on Voyager? What would you send on a spacecraft about to be launched into forever?

The calculator on your desk is more powerful than the computers on board the Voyagers. When the computers fail, only the information inscribed on the spacecraft and on the record will remain. Will these lonely space travelers reach other stars? In what condition? Will the record still work? Would others understand how to play the record? Can robotic travelers adequately replace humans in the exploration of space? Should we continue projects such as SETI (the Search for Extra Terrestrial Intelligence)? We climb the tallest mountains, submerge ourselves into the depths of the ocean chasms, and even hope to travel to distant worlds to see what is there; we have never ceased from exploration and discovery-only the destinations of our journeys have changed.

SPACE TALK

Planets, referred to as "wandering stars" by the ancient Greeks, are celestial bodies that orbit stars, have sufficient mass for self-gravity to assume a nearly round shape,and have cleared away the debris in the vicinity around their orbits.

A **satellite** (or **moon**) is a small body in orbit around a planet. If mathematical calculations show that an object is more gravitationally bound to the Sun than the planet it is orbiting, then that object is a planet, technically speaking. This is the situation with the Earth and its Moon. Several characteristics of the Earth-Moon system distinguish it from the satellite systems of most other planets in the Solar System, including the unusually large relative size of the Moon, its great orbital distance from Earth, and the fact that the Moon's path around the Sun is always concave to the Sun, like that of the Earth (but unlike that of most other satellites in the Solar System). As a result, some observers hold that the Earth-Moon system is a *double planet* rather than a planet with a satellite. Several possible planetary systems have been discovered orbiting other stars. We are not unique in the galaxy; we have only just developed the technology to detect such small objects so very far away. The planets and moons within our **Solar System** exhibit an extraordinary range of temperature, meteorology, size, and composition. Each is unique, from the sulfuric acid-laden clouds and lead-melting temperature of Venus, the vulcanism driven by tidal forces on Io, the methane lakes of Titan, to the giant hurricanes of Jupiter and the dust storms of Mars.

Other inhabitants of our Solar System which attract our attention are **comets**, referred to as "hairy stars" by the ancient Greeks. Once considered omens of impending disaster, these occasional visitors to our night sky now dazzle and delight us with their ghostly beauty as they shed dust and debris for millions of kilometers across the sky. Comets are composed of frozen ices such as water, carbon dioxide, methane and ammonia, along with fragments of minerals. Since it is not known if they have a higher percentage of minerals or ices, they can be thought of as either dirty iceballs or icy dirtballs! Long-period comets begin their journey towards the Sun from the **Oort cloud**, thought to exist at the farthest reaches of the Solar System and extending two light-years into space, halfway to the nearest star. Shorter-period comets come from the **Kuiper belt**, located beyond the orbit of Uranus. Comet Halley comes from the Kuiper belt; Hyakutake and Hale-Bopp probably originated from the inner Oort cloud.

Asteroids, also called **planetoids** or **minor planets**, are chunks of rock which are confined to the **asteroid belt** between Mars and Jupiter. However, some asteroids have Earth-crossing orbits and others, the Trojan asteroids, occupy the orbit of Jupiter. Sometimes asteroids get knocked out of the asteroid belt and travel through space. These stray asteroids are then called **meteoroids**, as are other chunks of rocky debris from sources such as Mars. If meteoroids should enter the Earth's atmosphere and heat up due to friction so we can see them, they are called **meteors**. Meteors that are large enough or have a high iron content can survive their fiery journey through the Earth's atmosphere and reach the ground. Then they are called **meteorites**. Very large ones gouge craters on the Earth's surface, such as the Barringer Crater in northern Arizona. So asteroids, meteoroids, meteors, and meteorites are all chunks of rocky materials; what they are called depends upon where you find them.

That leaves **meteor showers**, which are not meteors at all! Meteor showers are actually the debris left behind in the orbits of comets—the dust and metals left after the Sun's radiation unlocked them from the icy prison of the comet. When the Earth travels through the orbit the debris occupies, the debris heats up due to friction as it encounters the Earth's atmosphere, and is referred to as a meteor shower. Meteor showers are named after the constellations from which they seem to originate, such as the **Perseid** shower in August, which appears to come from the constellation Perseus.

Stars radiate their own energy because they have enough mass for thermonuclear fusion to take place in their core. Stars are unique, differing in color, temperature and mass. Stars are born and stars die; some are just emerging from their stellar nurseries, while others are in the later chaotic stages of life. Some stars are unstable and vary in temperature and brightness.

Milky Way Galaxy

And now we begin our journey from our star, the Sun, with its family of planets, moons, comets and asteroids, to learn about other stars. There are more stars in the **Milky Way Galaxy** than grains of sand on the surface of a beach. We shall learn to decipher the messages encoded within the light they radiate, as well as appreciate their eternal grace and beauty.

Unit 1: PLANETS AND STARS

Unit 1 is a descriptive introduction to our Solar System and the properties of the stars that lie beyond. Chapter 1, "The Solar System and Beyond," will help students develop a feel for the sizes of objects within the Solar System as well as the distances between them, and distances between the Solar System and stars within our galaxy. Chapter 2, "The Nature of Stars," discusses the stars' properties that are of primary importance to astronomers. These properties include size, brightness, and temperature, as well as their interrelationships. The knowledge and methods presented in this unit are the first steps on the road to becoming knowledgeable about astronomy, and perhaps to becoming an amateur astronomer!

CONTENTS FOR UNIT 1

Chapter 1: The Solar System and Beyond

An introduction to the nature, size, and scale of the Solar System and its place in the Milky Way Galaxy, along with some activities for expressing and visualizing these sizes and scales.

Chapter 2: The Nature of Stars

An introduction to the basic physical properties of stars that affect their appearance: apparent brightness, distance, temperature (seen as color), and the relationships among these properties.

Relationship to National Science Standards and Benchmarks

In Unit 1 we develop the unifying theme of “systems” by treating the Solar System as an organization of planetary bodies around a central star. Here we use a model as a method of understanding a system too large for visual observation. We show how several models can be used to represent the same thing, and that the scale of the models will determine their usefulness. The *Earth and Space Science Content Standard* states that by the end of eighth grade, students should develop an understanding of the Earth and Sun as an organized system, and be able to construct models that explain the physical relationships among the objects within the system. By the end of the twelfth grade, students should have acquired the ability to use observational data to continue inquiry into space science, even when things such as large distances are not directly observable. Students should also begin exposure to mathematics as a precise language used to describe objects, compare numbers of different sizes by expressing them as powers of 10, estimate sizes and distances, label numbers with appropriate units, and have the ability to convert units. This unit combines simple observations, basic knowledge, ideas, and open-ended questions to establish the basics of scientific inquiry. Especially in astronomy, students need to understand “how we know what we know.” They should gain the confidence to use mathematical models to determine information. Eighth graders should know that light from the Sun (or any star) is made up of a mixture of different colors. All students should know that stars differ from each other in size and temperature, and that they behave according to well-defined physical principles.

Chapter 1: The Solar System and Beyond

Summary

Chapter 1 introduces the nature, size, and scale of the Solar System and its place in the Milky Way Galaxy, and includes some activities for expressing and visualizing these sizes and scales. This chapter is an excellent introduction to the *Hands-On Astrophysics* curriculum. It can also stand alone as an interesting mathematical approach to scales and ratios, fractions, powers of ten and scientific notation, exponents and estimation, or as a discussion of the purpose for the development and use of models to explain large- or small-scale phenomena.

Terminology

asteroid belt	meteorites	minor planets	planetoid
asteroids	meteoroids meteors	Oort Cloud	satellite/moon
astronomical unit (AU)	meteor showers	Perseid	Solar System
comets	Milky Way	planet	star
Kuiper belt		planetary system	

Common Misconceptions About the Solar System

1. *The actual difference in size for Solar System objects is small.*
2. *The orbits of the planets are equally spaced.*
3. *The spacing between planets is not much larger than the diameters of the planets themselves.*

SUGGESTIONS FOR THE POSTER PAGES, INVESTIGATIONS, AND ACTIVITIES

NOTE: All numeric values in the student pages use the metric system, which is the universal standard for precise measurement. All scientific measurements use the metric system, making it easy to repeat measurements anywhere and anytime. The United States officially recognizes the metric system and science and industry use it extensively. It is a much simpler system of measurements than the English system, but there is a great deal of hesitancy here to completely convert to metrics. Resistance to change, and probably even more important, the far-reaching economic implications of instituting the conversion, have slowed the inevitable. Sometime in the future we will have to change. This unit does not start with a tutorial on the metric system. It is introduced, throughout the curriculum, only on a need-to-know-and-use basis. This should help the students assimilate the metric system more easily. For your information, the English equivalents of the metric value are given in parentheses. You can choose how to share this information with your students. Familiarity with a system means having an intuitive feel for what the numbers represent, and they may need to know the corresponding values in the English system until they become familiar with the metric equivalents. The students should become more comfortable with the system after encountering it in this chapter and those that follow.

Poster Page: Who Is More Important? (Kepler and Brahe)

Johannes Kepler and Tycho Brahe are interesting personalities. The contrast in traits between the wealthy, noble, arrogant Brahe and the independent, withdrawn, and poverty-stricken Kepler resulted in a strained and tension-filled relationship between them. Research into their different and colorful lives will provide excellent material for term papers, book reports, and exploration of two totally different contributions to the scientific process. The backdrop of the 30 Years' War and the upheavals and religious persecution of the early 1600s will place the work of these two astronomers into a historical context. Students will be surprised to hear that the Roman Empire's line of emperors was still being maintained in exile by its descendants a thousand years after the fall of the Empire. Superstitions, alchemy, and beliefs in astrology held sway over the population. Astrologers were powerful. The interrelationship of astronomy and astrology is a subject within itself—indeed, many astronomers spent most of their time writing horoscopes to support themselves. Another aspect of historical context is the plague, rampant throughout this time and playing a significant role in the life of Kepler and others. Tycho's metal nose is always intriguing to students (particularly as it involves dueling)—how did one manufacture different metallic noses and attach them in the early 1600s? What was the state of their metallurgy? Tycho's grave was exhumed to see if the story about the nose could be verified. Is this a good reason to dig up a grave? What procedures have to be followed for exhumation? Students can explore the origin of science fiction; for an interesting avenue of discussion they could research how Kepler came to write his science fiction story "*Somnium,*" about a trip to the Moon. Several astronomers throughout history have also written science fiction. Another rich topic is the role nations and governments play in supporting, controlling, or withholding support of scientific and scholarly research and freedom of thought.

Investigation 1.1a: Estimating Sizes and Distances

Give each group of students a box with an assorted collection of objects. You may decide to project the following data table (Table 1.1) on an overhead. Ask the students to identify the object in their box that corresponds to the Sun. They can then select the objects which represent the planets by using the data in Table 1.1.

Table 1.1		
Object	**Equatorial Radius**	
	(km)	**(miles)**
Sun	696,000	431,520
Mercury	2,440	1,513
Venus	6,052	3,752
Earth	6,378	3,954
Mars	3,397	2,106
Jupiter	71,492	44,325
Saturn	60,268	37,366
Uranus	25,559	15,846
Neptune	24,764	15,354
Pluto	1,151	714

Note: By convention, the *radius*, not the *diameter*, of a planet is usually listed in tables because it is used more frequently in mathematical relationships.

For example, the volume of a sphere ($V= 4/3\pi r^3$). Remind your students that they will need to double the radius to calculate the diameter.

Not all groups have to be given the same set of objects. More than the necessary amount of objects can be included to increase the difficulty of the sorting exercise. Another variation is to have the students find objects in their environment which correspond to the sizes of the planets after showing them a volley ball or cantaloupe to represent the Sun. You may elect to glue the objects representing planets onto cards, and insert the pins through pieces of cardboard so they are easier for students to handle.

This activity can be extended into a distance scale as well. Have the students discuss where to place the planets from the Sun using the same scale ratio used for the sizing of the planets. It is surprising that only Mercury, or maybe Venus depending on the size of the room, will fit inside the classroom. You will have to go outdoors, and have already selected a site approximately the length of 10 and a half football fields — ~950 meters (~1050 yards).

Estimation is a powerful skill, and even though this is not a core activity, choosing either this activity and/or one of the following activities is strongly suggested, as they are highly visual and directly address misconceptions involving size and distance.

Some suggested collections of objects:	**The distances are as follows:**
Sun: volleyball, cantaloupe; 20.5 cm (8.0 inches)	
Mercury: pinhead; .07 cm (.03 inches)	Mercury: 9.6 m (22.8 feet)
Venus: peppercorn; .20 cm (.08 inches)	Venus: 16.7 m (39.8 feet)
Earth: peppercorn; .20 cm (.08 inches)	Earth: 23.9 m (56.9 feet)
Mars: pinhead; .07 cm (.03 inches)	Mars: 35.8 m (85.2 feet)
Jupiter: chestnut; 2.30 cm (.90 inches)	Jupiter: 119.5 m (284.5 feet)
Saturn: hazelnut, acorn; 1.79 cm (.70 inches)	Saturn: 227.0 m (540.5 feet)
Uranus: peanut, coffee bean; .77 cm (.30 inches)	Uranus: 454.1 m (1081.2 feet)
Neptune: peanut, coffee bean; .77 cm (.30 inches)	Neptune: 717.0 m (1707.2 feet)
Pluto: pinhead; less than .07 cm (.03 inches)	Pluto: 956 m (2276.2 feet)

Investigation 1.1b: Sizing the Earth-Moon System

Students have misconceptions regarding the Earth-Moon system, since most illustrations are not accurate representations. Even though the Moon is the second-largest satellite in our Solar System, it appears relatively small next to the Earth. The Moon has one quarter of the Earth's diameter and approximately one-fiftieth of its volume. (From this, students tend to acquire the misconception that the Moon is one-quarter the *size* of the Sun.) In addition, the Moon's distance of thirty Earth diameters is visually impressive and usually quite a surprise to students, even if they "know the numbers" representing these distances.

Draw a 40-cm (16-inch) diameter circle on the board and label it Earth. Have the students predict the size of the Moon relative to this Earth circle, and have some of them draw their Moon circles on the board. Ask them to estimate how many Moons would fit into the Earth. After predictions have been discussed, explain that the true diameter of the Moon is about one-quarter of the diameter of the Earth. Therefore a 40-cm (16-inch) diameter Earth has a 10-cm (4-inch) diameter Moon. The following can either be done by groups of students or as a demonstration. Using a large piece of modeling clay, make 51 equal-sized balls of clay. Play-Doh™ can also be used; three cans with 17 balls made from each can will produce 51 balls.

Ask the students how many of the balls should be joined together to form the Earth and how many should be joined to form the Moon. Then take 50 of the balls and roll them into a single large ball. The large ball is a model of Earth and the single remaining ball is a model of the Moon. Ask students to comment on the relative sizes of the Earth and Moon. Even though they know that the diameter of the Earth is four times the diameter of the Moon, the difference in volume is usually a surprise! Explain that this is a properly-sized scale model of the Earth-Moon system and that fifty Moons are required to fill the same volume as the Earth.

Now ask the students to estimate the distance between the Earth model and the Moon model by indicating where the Moon should be placed relative to the Earth. After several estimates have been recorded, take a long piece of string and with one end measure the diameter of the Earth. Then fold the string back on itself repeatedly until the length is equal to thirty times the diameter of the Earth (3.81 m or 3.02 yards). Stretch out the string and then place the Moon at the appropriate distance. This is now an accurately scaled model of both size and distance for the Earth-Moon system.

This model should be left on display to reinforce the sense of scale. To help illustrate the scale, ask students how far from the Earth the Space Shuttle orbits. The shuttle orbits at a maximum altitude of 480 km (300 miles). If the Earth models that were created are approximately 12.5 cm (5 inches) in diameter—as they will be if the students used the Play-Doh™—insert a toothpick into the Earth model until just about 3½ mm (1/8th of an inch) is sticking out. This represents the altitude at which most satellites, including the Space Shuttle, orbit above the Earth. Also, ask the students what distance they estimate Apollo 13 was from the Earth when they transmitted the message: “Houston, we have a problem.” They will be quite surprised to find it was about two thirds of the distance between the Earth and Moon (2.55 meters or 2.02 yards).

Investigation 1.1c: Sizing the Sun and Planets

Students commonly have misconceptions regarding the actual sizes of objects within the Solar System. The numbers involved are usually meaningless, and the problem is compounded by misleading pictures and diagrams in textbooks and posters. Using a scale with 2.5 cm (1 inch) representing 4030 km (6500 miles) produces a model with the smallest possible Pluto and the largest possible Sun that can be dealt with in the classroom. The Sun must be created beforehand. Using tape and lengths of paper, construct a 3.45-meter (11.5-foot) diameter Sun and spray paint it a realistic yellow/ orange color. You may again choose to use this activity as a demonstration or involve groups of students. The planets should be cut out of black construction paper, and the comparative sizes discussed. Then ask the students how big the Sun should be if it is on the same scale as the sizes of the planets. Answers will vary. After discussing the possibilities, bring out the 3.45-meter Sun and display the Sun on the floor or the wall.

SIZE OF PLANETS		
MERCURY	1.2 cm	(.5 inches)
VENUS	3.0 cm	(1.2 inches)
EARTH	3.2 cm	(1.2 inches)
MARS	1.7 cm	(.67 inches)
JUPITER	35.0 cm	(13.8 inches)
SATURN	30.0 cm	(11.8 inches)
URANUS	12.7 cm	(5.0 inches)
NEPTUNE	12.3 cm	(4.8 inches)
PLUTO	.63 cm	(.25 inches)

Have the students tape the planets on the Sun. The size difference is remarkable and always surprising! The Sun can also be constructed of cloth or felt. The planets can be made of paper or felt. They can be attached to the Sun by means of Velcro™, and then will last through many presentations. The slide set "Worlds In Comparison" gives accurate scale comparisons among Solar System planet and Moon sizes, as well as scales for geologic features (see Resource List for details.)

RESOURCE

Core Activity 1.2: Unit Conversion

This activity is essential if your students are not familiar with units and unit conversion, otherwise it can be skipped. The next activity will require unit conversions, as do some of the other activities. This technique is used extensively in chemistry and physics courses. High school physics texts usually have several practice problems utilizing conversions, if you need a resource for other problems. It is a simple technique; however, students seem to have difficulty understanding that units cancel just like numbers, and that equal values (such as 60 minutes and 1 hour) can be made into fractions in order to convert units, as it is the same as putting the number 60 over the number 60, which is equal to one.

Answers to practice problems:

1. $$\frac{150\ \cancel{\text{km}}}{\text{hour}} \times \frac{0.62\ \text{mile}}{1\ \cancel{\text{km}}} = \mathbf{93\ miles/hour}$$

2. $$300\ \cancel{\text{miles}} \times \frac{1\ \text{km}}{0.62\ \cancel{\text{miles}}} = \mathbf{4839\ km}$$

3. $$3{,}655{,}000\ \cancel{\text{cm}} \times \frac{1\ \cancel{\text{m}}}{100\ \cancel{\text{cm}}} \times \frac{1\ \text{mile}}{1690\ \cancel{\text{m}}} = \mathbf{22.7\ miles}$$

4a. $$\frac{7\ \text{miles}}{\cancel{\text{second}}} \times \frac{3600\ \cancel{\text{seconds}}}{1\ \text{hour}} = \mathbf{25{,}200\ miles/hr}$$

4b. $$\underline{7\ \cancel{\text{miles}}} \times \underline{1\ \text{km}} \times \underline{3600\ \cancel{\text{seconds}}} = \mathbf{40,\ 645\ km/hr}$$

4c. $$\frac{7\ \cancel{\text{miles}}}{\cancel{\text{second}}} \times \frac{5280\ \text{ft}}{1\ \cancel{\text{mile}}} \times \frac{3600\ \cancel{\text{seconds}}}{1\ \text{hour}} = \mathbf{133{,}056{,}000\ ft/hr}$$

4d. $$\frac{7\ \cancel{\text{miles}}}{\cancel{\text{second}}} \times \frac{1690\ \text{m}}{1\ \cancel{\text{mile}}} \times \frac{3600\ \cancel{\text{seconds}}}{1\ \text{hour}} = \mathbf{40{,}546{,}800\ m/hr}$$

5. $$35\ \cancel{\text{years}} \times \frac{365\ \cancel{\text{days}}}{1\ \cancel{\text{year}}} \times \frac{24\ \cancel{\text{hr}}}{1\ \text{day}} = \mathbf{306{,}600\ ft/hr}$$

6. Sample for a 15 year old who sleeps ~8 hours//night.

$$15 \cancel{\text{years}} \times \frac{365 \cancel{\text{days}}}{1 \cancel{\text{year}}} \times \frac{8 \text{ hours}}{1 \cancel{\text{day}}} = \mathbf{43{,}800\ hours}$$

NOTE: You may need to explain to your students that in this problem one “sleep day” is equal to 8 hours. They are not looking for the total hours in 15 years (in which case they would use 24), they are looking only for the number of “sleep hours” in 1 “sleep day” in order to calculate how many hours of total sleep there are in 15 years.

Core Activity 1.3: String Model of the Solar System

This activity involves the construction of a scale model of the Solar System. The largest available distance in your school will determine the scale that you and your students will develop. You can construct it to fit the longest distance in your classroom, hallway, gym, or outdoors. If your students are not familiar with the technique for developing a scale, you may wish to determine the scale one day, and measure and construct the scale model the following day. A distance of 100 meters (109 yards) produces a small but visually effective model.

For younger students, construct a distance scale model only. For older, more sophisticated students, you may want to have them actually construct planets with correct scale models. The caveat is that unless you have 0.6 km (0.37 miles) of space with which to work, it is impossible to have the two scales the same. Having two different scales for distance and size may reinforce misconceptions about the size of the Solar System. If you choose to have the students calculate a scale for planetary diameters, refer to the radius distances in Investigation 1.1.

This activity also requires conversion of units. If your students are not familiar with this skill, you will need to use the unit conversion practice set in Core Activity 1.2. Since the distances to the planets are large numbers, this is an excellent time to introduce the Astronomical Unit (AU), as the AU is also an example of a scale. The distance from the Earth to the Sun is approximately 150,000,000 km (93,000,000 miles) and is designated as 1 AU. With this distance scale the distances from the Sun range from 0.39 AU for Mercury to 39.4 AU for Pluto—much easier numbers with which to work. (The students can use the actual distances and convert from kilometers to meters to see the difference themselves.) Another variation of this activity is to have separate groups of students use different locations so they will all have different-sized scale models. Then they can discuss the relative usefulness of each of the models.

Sample Scale based on a distance of 100 m (79 yards):

Scaling Factor (100 m/39.4 AU) = 2.54

Planet	Ave. Distance From Sun (AU)	Ave. Distance from Sun (kilometers)	Scale Distance from Sun (meters)	Scale Distance from Sun (yards)
MERCURY	0.39	58,000,000	0.39 x 2.54 = 0.99	1.08
VENUS	0.72	108,000,000	0.72 x 2.54 =1.83	2.0
EARTH	1.00	150,000,000	1.00 x 2.54 = 2.54	2.8
MARS	1.52	228,000,000	1.52 x 2.54 = 3.86	4.2
JUPITER	5.20	778,000,000	5.20 x 2.54 =13.21	14.4
SATURN	9.54	1,430,000,000	9.54 x 2.54 = 24.23	26.7
URANUS	19.2	2,870,000,000	19.2 x 2.54 = 48.77	53.4
NEPTUNE	30.1	4,500,000,000	30.1 x 2.54 = 76.45	83.7
PLUTO	39.4	5,900,000,000	39.4 x 2.54 =100.08	109.5

Core Activity 1.4: Mathematical Estimation of Sizes and Distances

This activity utilizes ratios and unit conversion to develop appropriately-scaled models of the Solar System. The first two questions prepare the students to develop their own scale for a Solar System model. You may decide to have them construct and demonstrate their models. If so, they should discuss what aspects of the Solar System are misrepresented in their models. Different groups can compare different scale models and discuss which ones are more useful and why. Table 1 .2A includes both meter- and kilometer-scaled distances. However, if the students select a small object to represent the Earth, they may not need to convert their scaled meters into kilometers.

RESOURCE

The 20 minute video entitled “Powers of Ten” is an excellent and powerful introduction to this topic. The first portion of the video “Cosmic Voyage,” relating to scale, can also be shown. It is less technical and more visually attractive. (See Resource List for details.)

Answers

1. (student estimation)

   a) $\frac{15 \times 10^7 \cancel{km}}{14 \times 10^5 \cancel{km}} = 1.07 \times 10^2$ = **107 solar diameters**

   b) 2 mm x 107 solar diameters = **214 mm**

   c) $\frac{14 \times 10^5 \cancel{km}}{13 \times 10^3 \cancel{km}} = 1.07 \times 10^2$ = **107 times larger**

   d) $\frac{2\text{ mm}}{107}$ = **0.02 mm**

2. a) 107 solar diameters x 25 cm = **2675 cm**

   $2675 \cancel{cm} \times \frac{1\text{ m}}{100 \cancel{cm}}$ = **26.8 m**

   b) $\frac{\text{diameter of Sun}}{\text{number of Earths per Sun}} = \frac{25\text{ cm}}{107}$ = **0.23 cm**

   c) 26.8 m x 40 = **1072 m**

   d) 1072 m x 2 = **2144 m (2.144 km),** as the distance of Pluto from the Sun is the approximate radius of the Solar System

   e) $\frac{420 \times 10^6}{14 \times 10^5}$ = **300 times larger than the Sun**

   300 x 25 = **7500 cm (75 meters) diameter for Betelgeuse**

   f) 2675 cm x 250,000 = 668,750,000 cm

   $668{,}750{,}000 \cancel{cm} \times \frac{1\text{ m}}{100 \cancel{cm}}$ = **6,687,500 m**

   $6{,}687{,}500 \cancel{m} \times \frac{1\text{ km}}{1000 \cancel{m}}$ = **6,688 km**

   g) Any location 6,688 km away, or

   $6{,}688 \cancel{km} \times \frac{0.62\text{ miles}}{1 \cancel{km}}$ = **4147 miles away**

3. The answers will vary depending upon the object selected.

Poster Page: An Arm's-Length Reach into the Universe (the Voyagers)

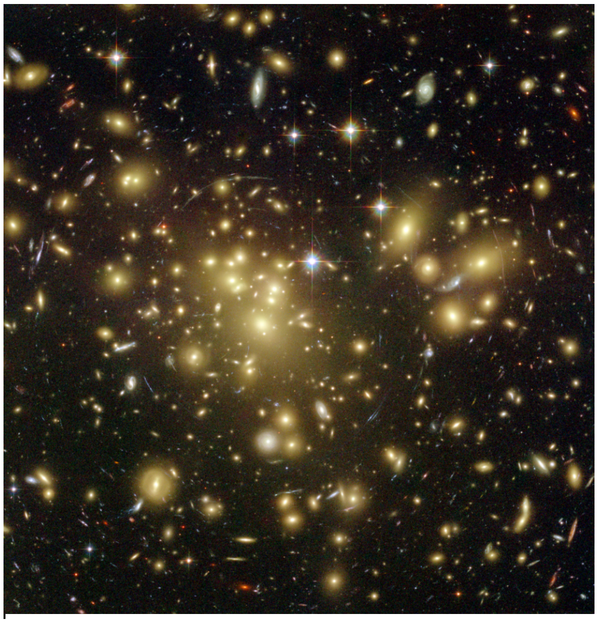
Many people are now unaware of the spacecraft probes Pioneer 10 and 11, and Voyager I and II as they continue their journey out of the Solar System. Robotic spacecraft, exploration of the Solar System and other possible planetary systems, and so on, are rich topics for discussion, involving the complex relationship among national goals, international competition, economics, and logistics combined with the fascinating prospect of reaching worlds beyond our own. Is it feasible? What is the cost compared to other national expenses, such as war or human services or education? Is it important? There have been many technological advances within our culture that are a direct result of space research. Students would be surprised at the improvements they enjoy because of the NASA aerospace program, such as changes in medicine, engineering, and manufacturing. Many do not realize that such things as the amount of rainfall, the tracking of herds of migrating animals, and the rate of movement of the continental plates are now all measured from space.

The desire to explain our culture to any alien culture that might encounter the Pioneers and Voyagers suggests that science fosters human and hopeful endeavors. If your students launched a spacecraft, what would they include? Research all the information sent into space so far. Would they select sounds? What sounds? Would they select music? If so, would it be the same music? What do they think is representative of the planet? How would they convey, in an understandable fashion, the concept of what it is like to be human? Is that even possible? Is it even worth attempting? We bury time capsules under buildings and near statues in parks. What is buried? Why? Are time capsules in the ground similar to time capsules in space? What are we trying to say, and whom are we trying to tell?

SETI—the Search for Extraterrestrial Intelligence—is an active program. Is there other life orbiting around other suns within our galaxy? Should we spend time and resources on such a search? Several possible extrasolar planets have been discovered, all very unlike Earth. Research these planets and their suns. What types of life-forms could exist under those conditions? Could the same compounds survive there that have developed into complex living systems here on Earth? Do these planets meet your definition of a planet?

A plethora of creative writing and art projects, especially construction of models, are worthwhile extension activities associated with robotic exploration and the SETI program. Compiling a list of information and how to communicate it to alien beings involves consideration of multicultural and historical expressions of humankind.

Chapter 2: The Nature of Stars



Galaxy Cluster Abell 1689 (HST Image)

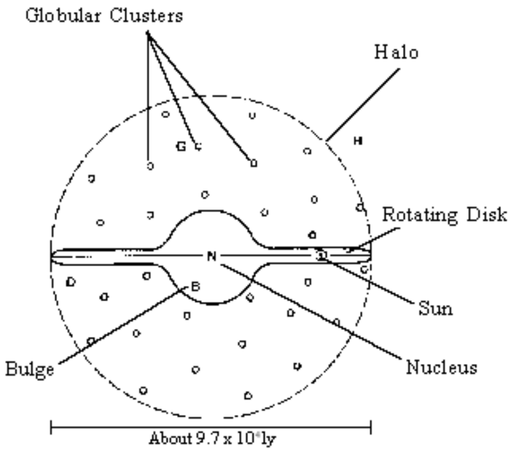
Introduction

Beyond our Sun and Solar System exist billions of other stars traveling around the center of the Milky Way Galaxy. If you go to a site away from city lights and stare up at the night sky when the Moon is not up, you will be able to see, ideally, about 3,000 of these stars during a single night of observation with the unaided eye. What can be seen or not seen depends upon the surrounding environment: light and air pollution, convection currents, weather, the brightness of the stars, and the acuity of the observer's vision. You will notice too that the stars vary in appearance.

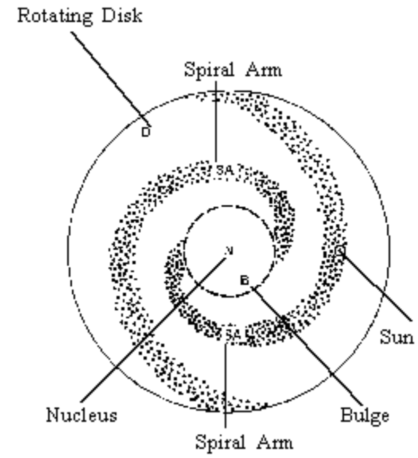
All the stars you see lie within the disk of the Milky Way Galaxy. It is a typical *spiral galaxy* with prominent arms of gas, dust, and stars (see Figure 2.1 on the next page). The nuclear bulge—a dense concentration of stars surrounding a massive black hole—lies in the direction of the constellation Sagittarius. Within the disk some stars are solitary, others are gravitationally-bound multiple star systems. There are also special groups of stars, open clusters, and globular clusters. Open clusters are located within the disk of the galaxy. They are groups of stars which were born within the same condensing cloud of gas and dust. Although they are still gravitationally associated with each other, they have their own motions and will slowly drift farther and farther apart. A familiar example of an open cluster is the Pleiades, which precede Orion into the autumn and winter sky. Globular clusters are tightly packed, spherically symmetrical groups of stars located outside the disk, within the galactic halo, and are also thought to share a common origin. However, unlike open clusters which contain young stars, globular clusters contain older stars, much older than the Sun, and are thought to have formed early in the life of the Milky Way.

Our Sun and Solar System occupy the Orion Arm of the galaxy, 30,000 light-years away from the galactic center. As part of the Orion Arm, the Solar System orbits around the galactic center once every 250,000,000 years (one galactic year). If the spiral arms—carrying their stars, dust, and gas—orbit around the galactic center in the same manner that the planets orbit around the Sun, then the spiral arm structure should no longer exist. The farther away from the center, the slower the arms should rotate. The spiral arms should have wound up and formed a disk by now. How spiral galaxies maintain their spiral arm structure is a puzzle. Astrophysicists are still trying to solve this mystery.

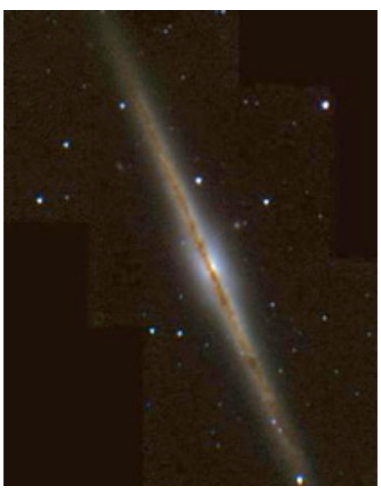
On a clear night, from the Northern Hemisphere, we can catch a small glimpse of our sister galaxy, the Andromeda Galaxy. Although Andromeda is similar in size to our Milky Way, it appears as a fuzzy patch with no individual stars discernible. Even though it is nearby, the light we see from this galaxy has traveled through space for two million years before reaching planet Earth. We always see the Andromeda Galaxy the way it looked two million years ago—we will never be able to see it the way it looks at this moment!



An edge-on schematic view
of our Milky Way galaxy



A face-on schematic view
of our Milky Way galaxy

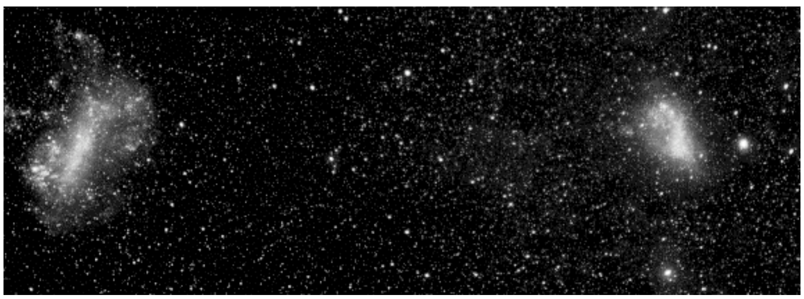


Edge-on view of NGC 891, a spiral galaxy with features simlar to our Milky Way

Face-on view of M74, a spiral galaxy with features similar to our Milky Way galaxy, (Gemini Observatory, GMOS)Team)

Figure 2.1

From the Southern Hemisphere, two more companion galaxies much closer to the Milky Way are visible, the Large and Small Magellanic Clouds, 160,000 and 195,600 light-years away, respectively. The Large Magellanic Cloud (LMC) has one-fifteenth the mass of the Milky Way, and the Small Magellanic Cloud (SMC) has one-sixth the mass of the LMC. They are ragged in appearance and classified as irregular galaxies, as they have no specific shape or structure. These galaxies were named after Ferdinand Magellan during his voyage around the world in 1512. Magellan's historian on the voyage, Ernesto Pigafetta, officially described and recorded these objects, though they had been used previously by Portuguese navigators during the 1400's to locate the direction of the South Pole. The Portuguese referred to them as Cape Clouds, because they came into view as their ships approached the Cape of Good Hope. For the next three hundred years these galaxies were thought to be clouds within our own galaxy.



The Magellanic Clouds are satellite galaxies, close enough to the Milky Way Galaxy to be severely affected by its gravitational field. Both have had close encounters with the Milky Way, and the Small Magellanic Cloud has been seriously disturbed by these interactions. Both the LMC and the SMC are embedded in a loop of hydrogen gas that extends into the Milky Way from a recent encounter. As a result of these interactions, the SMC is deteriorating, not having enough mass to hold onto its gas and dust, which are necessary ingredients for manufacturing new stars. The SMC will eventually be absorbed by both the LMC and the Milky Way—the price a low-mass galaxy pays when it strays too close to its more massive companions. The tranquil appearance of our galaxy is indeed misleading, as it is even now in the process of obliterating one of its own neighboring galaxies. The Milky Way Galaxy and the Magellanic Clouds are locked into a cosmic dance with gravity.

Galaxies are bound together in clusters. The Milky Way, Andromeda, the LMC and SMC, are only four of the approximately twenty-four galaxies that comprise the cluster known as the Local Group. Clusters of galaxies are gravitationally bound into the largest associations in the universe—superclusters. The Local Group belongs to the Virgo Supercluster. Sky surveys show that superclusters are not uniformly spread throughout the universe, but cluster around the edges of large spherical empty spaces.

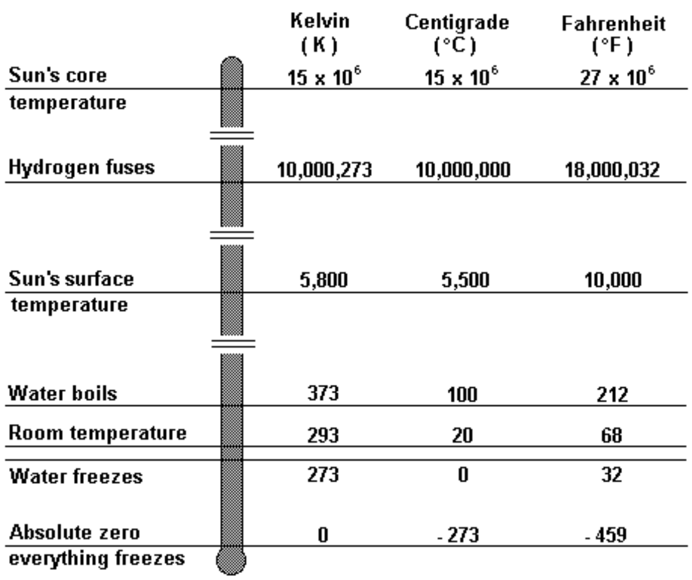
Investigation 2.1: The Properties of Stars

Look at the slide of a star field in Cygnus below. Do all the stars in the field look the same? What are some differences? Make a list. What properties of stars do you think would cause these differences?

Star Field in Cygnus

Core Activity 2.2: Understanding the Temperature Scales

Temperature scales are constructed by assigning numbers to certain points where, for example, water freezes or boils. The most common scale used in the United States was developed by Gabriel Fahrenheit in 1714. This scale was originally standardized by assigning the value 98.6 to the normal temperature of the human body and establishing this as the high end of the scale. The lower end was established by assigning a temperature of zero to an ice water solution that contained salt, as salt water has a lower freezing temperature than pure water. The Fahrenheit scale has been modified so that the upper limit is standardized as the point at which pure water boils at sea level (212 degrees) and the lower limit at 32 degrees, the freezing point of pure water. The Celsius scale, commonly used throughout the world, was developed by Anders Celsius in 1742. This scale assigns 100 degrees as the boiling point of pure water at sea level and zero degrees as the freezing point.



A different scale is used by scientists, called the *Kelvin (K) scale*. This scale is not arbitrary: the zero point of the Kelvin scale is -273^{o}C or absolute zero—the point at which all molecular motion (kinetic energy) ceases. This is the lowest possible temperature an object can reach. Since the zero point of the Celsius scale is the freezing point of water, and the zero point of the Kelvin scale is absolute zero, and these two scales are separated by 273, the conversion from one of these scales to the other is simply the addition or subtraction of 273. (From ^{o}C to K, add 273; and from K to ^{o}C, subtract 273.) NOTE: The Kelvin scale is based upon kinetic energy, a measure of molecular motion, and therefore does not have a "degree" symbol

Temperature Conversion Relationships

From	**To**	**Formulae**
Fahrenheit	Celsius	$T_c = 5/9(T_f - 32)$
Celsius	Fahrenheit	$T_f = (9/5\ T_c) + 32$
Celsius	Kelvin	$T_k = T_c + 273$
Kelvin	Celsius	$T_c = T_k - 273$

1. The average body temperature for humans is 98.6 °F. What is this temperature in Kelvin?

2. Determine the temperature of your room in Fahrenheit, Celsius, and Kelvin.

3. The Moon's temperature on its bright side is 100 °C and on its dark side is –173°C. What are the corresponding temperatures in Fahrenheit and Kelvin?

4.

   a. The surface temperature of the Sun is 5770 K. What is the equivalent temperature in Fahrenheit?

   b. This temperature may seem very high indeed. However, the bright star Rigel in the constellation of Orion the Hunter is a hot, bright white star with a surface temperature of ~12,000 K. How much hotter is Rigel than the Sun?

5.

   a. The hottest stars in the night sky shine with a bluish color and have temperatures in the range of 30,000–60,000 °C. Express this temperature range in Kelvin and Fahrenheit.

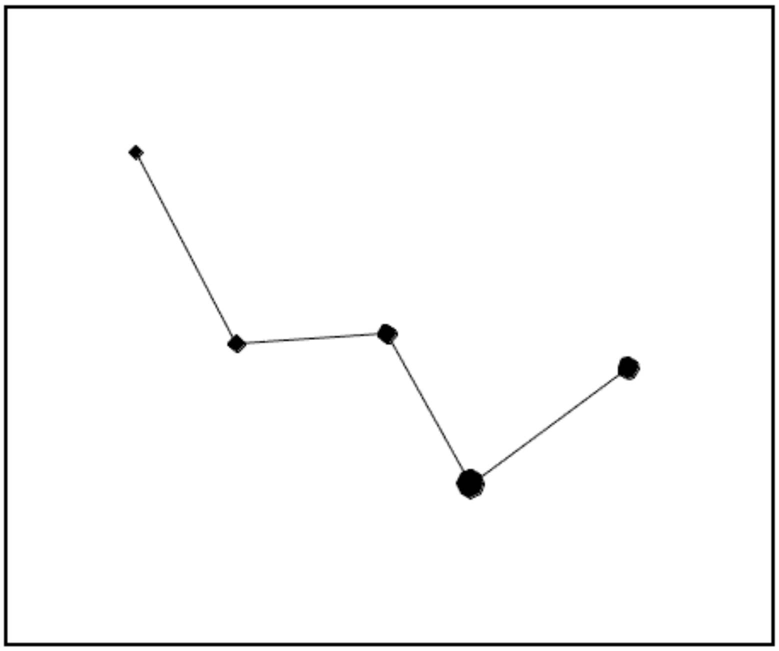
   b. Cool red stars have temperatures of about 3250 °C. Express this value in Kelvin and degrees Fahrenheit.

6. Outer space is filled with huge voids between individual stars, and even between galaxies and between clusters of galaxies. The temperature within these voids is essentially 3K, which is the temperature of the cosmic background radiation. Convert this temperature to Celsius and Fahrenheit.

7. Some variable stars pulsate through a range of temperatures. One such star, the omicron star from the constellation Cetus the Whale, varies from ~4500 K to 2400 K. What is the corresponding change in °F?

8. Why is the Kelvin scale useful? Why is it used instead of Celsius for stellar atmospheres? Would the Kelvin scale be useful instead of the Fahrenheit scale for everyday purposes? Why don't our thermometers use this scale?

Given below is a sketch of the five brightest stars in the constellation Cassiopeia. In this sketch, as in other star charts, the stars are represented by points of different sizes. Although we cannot discern the relative sizes of the stars in the sky, this method of representing stars by different point sizes is used to indicate the relative brightness of the stars. The larger the point, the brighter the star is in the night sky. In the sketch below, rank the stars in order of brightest to dimmest on a scale of one to five with one being the brightest, and five being the dimmest.

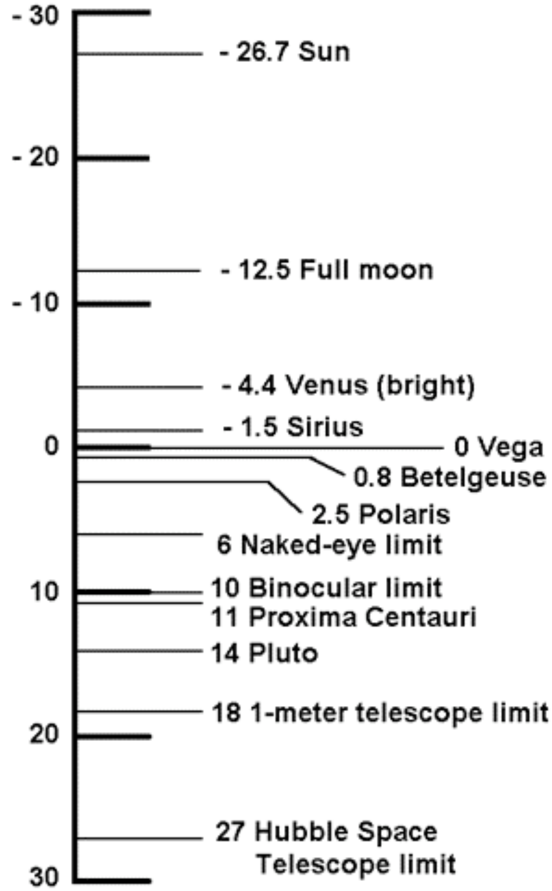


Repeat this activity with a slide of Cassiopeia. If you are able to observe this constellation at your location, you may wish to rank the stars by direct observation.

Measuring the Brightness of Stars

If you have observed the night sky, you have noticed that some stars are brighter than others. The brightest star in the northern hemisphere winter sky is Sirius, the "Dog Star" accompanying Orion on his nightly journey through the sky. In the constellation of Lyra the Harp, Vega shines the brightest in the summer sky. How bright is Sirius compared to its starry companions in the night sky? How does it compare to Vega, its counterpart in the summer sky? How bright are these stars compared to the light reflected from the surface of the Moon? From the surface of Venus?

The method we use today to compare the *apparent brightness* of stars is rooted in antiquity. Hipparchus, a Greek astronomer who lived in the second century BC, is usually credited with formulating a system to classify the brightness of stars. He called the brightest star in each constellation "first magnitude." Ptolemy, in 140 AD, refined Hipparchus' system and used a 1 to 6 scale to compare star brightness, with 1 being the brightest and 6 the faintest. Astronomers in the mid-1800's quantified these numbers and modified the old Greek system. Measurements demonstrated that 1st magnitude stars were 100 times brighter than 6th magnitude stars. It has also been calculated that the human eye perceives a one magnitude change as being 2½ times brighter, so a change in 5 magnitudes would seem to be 2.5^5 (or approximately 100) times brighter. Therefore a difference of 5 magnitudes has been defined as being equal to a factor of exactly 100 in apparent brightness.



Magnitudes of Selected Objects

It follows that one magnitude is equal to the fifth root of 100, or approximately 2.5; therefore the apparent brightness of two objects can be compared by subtracting the difference in their individual magnitudes and raising 2.5 to the power equal to that difference. For example, Venus and Sirius have a difference of about 3 magnitudes. This means that Venus appears 2.5^3 (or about 15) times brighter to the human eye than Sirius. In other words, it would take 15 stars with the brightness of Sirius in one spot in the sky to equal the brightness of Venus. Sirius, the brightest apparent star in the winter sky,and the Sun have an apparent magnitude difference of about 25. This means that we would need 2.5^{25} or about 9 billion Sirius-type stars at one spot to shine as brightly as our Sun! The full Moon appears 10 magnitudes brighter than Jupiter; 2.5^{10} equals 10,000, therefore it would take 10,000 Jupiters to appear as bright as the full Moon.

On this scale, some objects are so bright that they have negative magnitudes, while the most powerful telescopes have revealed faint 30th-magnitude objects. The Hubble Space Telescope can “see” objects down to a magnitude of about +30. Sirius is the brightest star in the sky, with an apparent magnitude of –1.4, while Vega is nearly zero magnitude (–0.04).

Core Activity 2.4: The Apparent Colors of Stars in the Night Sky

You will be shown some constellations, star fields, or other pictures of the night sky. You will be given three different colored filters. For each picture, write your observations in the table below of how the pictures appear when looking through each filter.

1. Look at one of the color slides or prints. Describe the brightness and colors of the objects it shows.

2. What types of stars or features of the pictures are more visible with the red filter? Why?

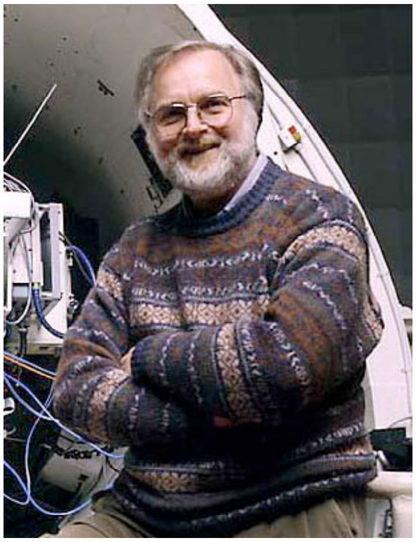
3. What features of the picture are more visible with the blue filter? Why?

4. Which filter changes the pictures least from your non-filtered view?

5. Human eyes are most sensitive to yellow, so red or blue objects appear dimmer to us when we observe them in the sky. Do you think humans have evolved in such a way that there is a relationship between this sensitivity and the color of the Sun?

SLIDE NAME	Red	Blue	Yellow
1.			
2.			
3.			
4.			
5.			

David Malin - The Man Who Colors the Stars



Like other great artists before him, David Malin is a great experimenter. Utilizing photographic film as his canvas, wielding a prime focus camera mounted in a cage attached to the Anglo-Australian Telescope as his brush, and with the entire cosmos displayed before him as his subject, David Malin has changed forever the way that we view the universe. The masterpieces in his cosmic portfolio adorn and beautify our world in books, and on posters, coffee cups, T-shirts, postcards, bookmarks, television, and postage stamps. Who has not seen his Horsehead Nebula image? It is captivating-the Mona Lisa of astronomical photography-luring us to contemplate what lies behind the seemingly calm exterior. David Malin is the world's foremost astrophotographer. He has given us a gift of rare and wondrous insight into the breathtaking beauty that otherwise would remain invisible to human perception.

Malin's legacy is one of color. His pictures are not only beautiful, but also valuable, full of priceless science. Utilizing glass plates 14 inches square, Malin takes three black and white exposures through separate colored filters of red, green, and blue. These are then superimposed onto photographic film, resulting in images of stars with their actual colors, thus giving an indication of their age, size, temperature and evolutionary history. Malin's images of nebulae and galaxies are a veritable feast of color and detail, painstakingly extracted from the glass plates with techniques he has developed. "There's color out there that explains the cosmos," Malin declares. The aim of his work is to unlock the information hidden within and behind the cosmic clouds of dust and gas to reveal a wealth of scientific insights.

David Malin's artistic ability to paint the universe is a powerful tool for scientific study. Science is the objective; the art only a delightful result. But it is a result which helps make the cosmos more understandable for us all.

Malin, sitting inside his prime focus cage with his back to the stars, listening to the music of Bach and Beethoven, bestows upon science an almost spiritual experience placing the details of rigorous research into the context of humankind's incessant search into cosmic distances for answers to ancient questions.

M20, The Trifid Nebula.
David Malin's photographic works brings out structures that no other techniques reveal. (Photo courtesy of David Malin, Anglo-Australian Observatory)

David Malin portrays the messages from the stars as scientist, artist, and astronomical historian. By producing images of the light echoes from the 1987 supernova in the Large Magellanic Cloud, Malin allows us to see in rich detail an event which occurred 160,000 years ago before Neanderthal Man emerged in southern Germany. Being able to see those light echoes, we are able to measure the rate of expansion of the supernova's resulting shockwave. Malin's paintings of starlight tell stories of ancient catastrophes, such as gas shell remnants around galaxies which show that two galaxies, trapped in gravitational warfare, have long since reconciled their fates and merged into one.

Bok globules seen against the faint nebula IC2944. These globules are small, dark, cool clouds of gas and dust which may produce low-mass stars.

Even the world's foremost astrophotographer has to settle for his own small allotment of precious telescope time, usually 5–8 nights a year, and sometimes some of those nights are cloudy. In the twenty years that David Malin has been at the Anglo-Australian Telescope, he has produced fewer than 200 pictures, some of which have taken years to produce. Malin produces spectacular images even with an ordinary hand-held camera because he is constantly experimenting, exploring, and developing new techniques. His star trails are brilliant; some, which have been progressively defocused, show the stars as trailing plumes of stellar colors. David Malin gives us visual proof that color helps to explain the cosmos.

David Malin grew up in a cottage without electricity in England's Lake District. His mother worked in a cotton mill, and Malin worked as a projectionist at the local movie house and as a caller in a bingo parlor. At the age of 15, Malin dropped out of school. Eventually he became a lab apprentice with the Swiss Chemical Company, where he re-established an abandoned photography darkroom. Malin took classes in physics, chemistry, and math at a technical college to maintain his position with the company, and used his knowledge to experiment with photography.

He had no formal education in astronomy and few qualifications for employment when he applied for work at the Anglo-Australian Telescope on Siding Spring Mountain, Coonabarabran, New South Wales, Australia. However, his self-acquired knowledge and expertise with photographic plates gained him the position. Always experimenting with different techniques to produce better and better images, never being completely satisfied, and forever seeking ways to extract more and more information from his glass plates, have earned David Malin his international reputation as the world's foremost astrophotographer.

David Malin is now at a photographic crossroads. Eastman Kodak has stopped making the 14-square inch glass photographic plates which Malin uses for his astrophotography. The world has become more technological and now CCD (Charge Coupled Device) cameras have replaced glass plates. We are all familiar with the beautiful CCD images provided by the Hubble Space Telescope (HST). Many would say that Malin and his glass plates are now outdated and old-fashioned. But Malin is not in competition with HST; his work, is complementary. As yet, CCD images cannot compete with Malin, cannot render the fine detail delivered by his special techniques. Yet CCD cameras are rapidly improving, and soon will have that ability.

The rapid advances in technology have resulted in an explosion of astronomical knowledge in the last two decades. Sometimes old methods must give way to new methods, and scientists must keep up with changing technologies. And so Malin has started producing images with CCD cameras. The reluctance of leaving behind the familiar is overshadowed by the excitement of new possibilities. Whether by glass plates or by CCD images, Malin will continue to bring us stunning views of the universe, and his images will have many cosmic stories to tell.

David Malin's photography reveals subtleties in the reflection nebula that is illuminated by the stars of the Pleiades.

(Photos courtesy of David Malin, Anglo-Australian Observatory)

So far only robot eyes have seen any farther than the Moon. As the Voyagers travel to the farthest reaches of the Solar System and beyond, they will eventually stop transmitting information and silently drift into interstellar space, no longer able to communicate with the hopeful civilization that launched them. If we were traveling with Voyager 1, now on its way past Pluto's orbit, the **apparent brightness** (**apparent magnitude**) of the Sun would be greatly diminished—even though its **actual brightness**, or **absolute magnitude**, would be the same. From this distance the Sun would be just another star, its life-sustaining energy too faint to impact the frigid outer reaches of the Solar System.

Voyager 1 has been traveling at 59,346 kilometers/hour for 20 years; however, that is an incredibly slow speed compared to the speed at which light travels. The six o'clock morning news broadcast would reach Voyager by three o'clock that same afternoon—traveling in 9 hours the same distance covered by Voyager in 20 years!

The Light-Year:
A Unit of Cosmic Distance

Because there is nothing known to travel faster than the speed of light, the light-year is the most convenient way in which to describe the very large distances and sizes we find in the universe.

The light-year is a unit of distance equal to the distance that light, radio waves, or any other form of electromagnetic radiation, travels through space in one year.

All electromagnetic radiation in a vacuum travels at the speed of light, 299,792 km/s. So at this rate, one light-year 12 equals 9.4605×10^{12} km (9.4 trillion kilometers, or about 6 trillion miles.) Distances expressed in light-years give the time that radiation would take to cross that distance. There are other ways of measuring distance in space, but the light-year is the unit of measurement used in most cases.

The light-year is the ideal way to describe astronomically large distances, but it can be applied to smaller distances as well. For example, the distance from the Sun to the Earth is about 8 light-minutes.

Speed of	km/s	Unit of Distance	Distance Travelled in 1 year
Light	299,792	1 light-year	9.4×10^{12} km
Voyager-1	16.485	1 Voyager-1 year	5.2×10^{8} km
Sound	0.331	1 sound year	1.0×10^{7} km
Jet Plane	0.223	1 jet year	7.0×10^{6} km
Fast Car	0.030	1 fast car year	9.4×10^{5} km
Person Walking	0.00089	1 person year	2.8×10^{4} km
Snake	0.00022	1 snake year	16.9×10^{3} km
Skunk	10.00002	1 skunk year	6.3×10^{2} km
Snail	0.0000004	1 snail year	1.2×10^{1} km

The nearest star is Proxima Centauri, 4.2 **light-years** away. At this distance, anybody listening to radio signals coming from Earth would be learning about the events taking place on this planet a little more than four years ago. But near Pollux, one of the twins in the constellation Gemini 35 light-years away, the news of John Glenn's orbit around the Earth in 1962 is now rushing past. Anyone near 13 Ceti, a 5th-magnitude star in the constellation Cetus, 53 light-years away, would now be hearing about D-Day, the beginning of the end of WWII when the Allies landed on the beaches of Normandy, France. Signals from Orson Welles' famous Halloween Eve broadcast of "The War of the Worlds" in 1938 are only now reaching tau Cygni, in the constellation Cygnus. (Do listeners on other worlds think that somewhere a planet called Mars is invading a planet called Earth?) Aldebaran, the very bright reddish-orange star in Taurus the Bull, is hearing about the stock market crash of 1929 marking the beginning of the Great Depression. 16 Cygni is now receiving the message that Charles Lindbergh is the first person to fly solo across the Atlantic Ocean in an airplane. Somewhere, some star 77 light-years distant is hearing America's first radio broadcast from 1920. Will anyone receiving these signals be able to understand them? And if so, will they know what an ocean is, or a stock market, or a war?

The **interstellar medium** between stars is so thin and tenuous that it is nearly a perfect vacuum. The few atoms and molecules that comprise the medium inhabit a frigid environment with a temperature of only 3 **Kelvin**—having so little kinetic energy that they barely move. It is also a silent environment, since sound requires a medium through which to travel. Light, which needs no medium, travels through the dark and cold, carrying its messages to and from distant stars and planetary systems hundreds and thousands of light-years apart. In places, great clouds of gas and dust, called **nebulae**, emit, reflect, or absorb radiation.

Leaving the plane of the **galaxy** with its huge spiral arm structure of rotating clouds of gas, dust, and stars, and traveling above or below the disk, we encounter an even less-occupied region of the Milky Way. Here is where the **globular clusters** reside. These clusters do not have enough mass to retain their gas and dust, and supernova explosions carry material away from the clusters. As globular clusters wander around the galactic halo, sometimes they travel through the disk, and lose even more material. Consequently the dust and gas necessary for making new stars is absent. Eventually the globular clusters will become galactic ghost towns, filled with the cores of dead and dying stars. Imagine living on a planet orbiting a star in a globular cluster and having a full-face, close-up view of the Milky Way Galaxy lighting up the entire night sky!

Virgo Supercluster

(Creekside Observatory, Embry Riddle Aeronautical University)

Light traveling through the Milky Way would take 100,000 years to get from one end to the other; 30,000 years to get from the center of the galaxy to the Sun; two million years to reach the shores of the Andromeda Galaxy from the Earth. To reach the edge of the Local Group **cluster** of galaxies, the light from the Milky Way Galaxy would take more than three and a quarter million years, and in excess of 65 million years to reach the heart of the Virgo **supercluster**. Light is the ultimate cosmic voyager, traveling for hundreds, thousands, millions, and billions of light-years to deliver ancient messages from the stars and galaxies to those with the ability to read them.

Chapter 2: The Nature of Stars

Summary

Chapter 2 introduces the basic physical properties of stars which affect their appearance: apparent brightness, distance, temperature (seen as color), and the relationships among these properties by utilizing slides, photographs, colored filters and/or the night sky. Students will investigate differences among the stars.

Terminology

absolute magnitude	clusters	light-year
actual brightness	globular cluster	nebulae
apparent brightness	interstellar medium	spiral galaxy
apparent magnitude	Kelvin	supercluster

Common Misconceptions About Stars

1. *All stars are the same color.*
2. *The North Star is the brightest star in the night sky.*
3. *All stars are the same distance from the Earth.*

SUGGESTIONS FOR THE POSTER PAGES, INVESTIGATIONS, AND ACTIVITIES

Investigation 2.1: The Properties of Stars

Show one of the HOA slides to the students. Have them list the differences they see, and think about what properties of stars could cause these differences. Size may be a common answer to this question, and size is indeed important. The greater the surface area of a star, the greater the amount of light or energy it emits. Since the area varies as the square of the radius, a star which has 3 times the radius of another star would emit 3 2 or 9 times the total light.

Size is only one variable that determines the actual brightness of a star; temperature is another. If your students have used a Bunsen burner, they already know that a yellow flame will deposit carbon on the bottom of a test tube because the flame is not hot enough for complete combustion of the gas. If a yellow flame is cool, a blue flame must be hotter, since it does not deposit carbon on the tube. So a yellow flame is cooler than blue, and blue is hotter than yellow. Similarly, when an electric stove element is first turned on, it is black. After a few minutes the element starts turning dark red, then at maximum high it is orange-red. The brighter the color, the hotter the burner. Stars have a similar temperature/ color relationship. Red stars are cooler (surface temperatures of ~ 3,000 K), yellow stars are hotter (surface temperatures of ~6,000 K), while white or blue-white stars are even hotter (surface temperatures up to ~50,000 K). The important concept for students to acquire is that color is associated with temperature.

Core Activity 2.2: Understanding the Temperature Scales

The following math conversion exercises are meant to help students understand the differences among the three temperature scales, Fahrenheit, Celsius, and Kelvin. It is likely that only students who have had chemistry or thermal physics will have been introduced to the Kelvin scale. Others may have encountered the Celsius scale, but are more comfortable with the Fahrenheit scale, especially if they have not completely grasped what Celsius temperatures mean relative to the Fahrenheit scale. The Kelvin scale is important in physical science; it is the only scale that is not arbitrary and is used for stellar temperatures. This activity is not necessary for students already familiar with the Kelvin scale.

Answers to the Exercises on Temperature Scales

1. $T_c = (5/9)(98.6 – 32) = 37^oC$; $T_k = 37 + 273 =$ **310K**

2. (Answers will vary)

3. $100^oC + 273 = 373K$; $T_f = (9/5)(100) + 32 =$ **212^oF**

   $–173^oC + 273 = 100K$; $T_f = (9/5)(–173) + 32 =$ **$–279^oF$**

4. a) $T_c = 5{,}770K – 273 = 5{,}497$; $T_f = (9/5 (5{,}497) + 32 = 9{,}927^oF$

   b) $12{,}000 – 5{,}770 = 6{,}230K$; $T_c = 6{,}230 – 273 = 5{,}957$

   $T_f = (9/5)(5{,}957) + 32 =$ **$10{,}755\ ^oF$ hotter.** Its surface temperature is **$20{,}682^oF$**

5. a) **30,273K – 60,273K (a 30,000K range),**

   $T_f = (9/5)(30{,}000) + 32 =$ **$54{,}032\ ^oF$ range**

   b) $T_k = 3{,}250 + 273 =$ **3,523K**; $T_f = (9/5)(3523) + 32 =$ **$6{,}373\ ^oF$**

6. $T_c = 3K - 273 =$ **-270^oC,** $T_f = (9/5)(-270) + 32 =$ **-454^oF**

7. $4{,}500K - 2{,}400K = 2{,}100K - 273 = 1{,}827^oC$;

   $T_f = (9/5)(1{,}827) + 32 =$ **$3{,}321^oF$**

8. There are various reasons. From the perspective of astronomy, the Kelvin scale is a thermodynamic temperature scale (absolute temperature scale)—that is, a temperature scale in which the temperature is a function of the energy possessed by matter. It is a measure of the total energy or power emitted by a star. When we read an outdoor thermometer, we are concerned with how "hot" or "cold" it is outside. When we take our temperature when our body is fighting an infection, we are concerned with whether our body is producing more "heat." Have your students calculate what the Kelvin scale would be for an outdoor or internal thermometer. Is it a convenient scale? Why or why not?

Investigation 2.3: How Bright Is It?

You may choose to do this activity with the drawing provided, followed by the slide, or by observation of the night sky.

Core Activity 2.4: The Apparent Colors of Stars in the Night Sky

Choose one of the HOA slides for this activity. Have pieces of red, blue, and yellow transparencies—such as the filters used in photography or in theatrical lighting, or colored cellophane. You will want to experiment with several slides to see which ones contain the colors that work best with your filters. The stars on the slides are small, and the difference the filters make may not be obvious to your students. You may want to start by using pieces of colored construction paper before using the slides, so that they can see how the filters change the appearance of red, blue, and yellow colors. Then the students can use the filters with the slide(s) you have selected.

This activity demonstrates the varying effects of red, blue, and yellow filters when viewing starlight. The apparent brightness of a star depends upon which part of the visible spectrum we are observing. Consider a blue and a red star, each of the same apparent brightness. If the two stars are observed through a red filter, the red star will appear brighter than the blue one. If they are both viewed through a blue filter, the blue star will appear brighter. Yellow filters match the strongest part of the visible spectrum and approximate normal vision. A standard set of filters is used in the analysis of starlight: the UBV set of filters (U for ultraviolet, B for blue, and V for visual, or yellow). The use of these filters gives two types of information: (1) the total magnitude of light from all spectral ranges, and (2) the color index which is used to calculate temperature.

Poster Page: The Man Who Colors the Stars (David Malin)

"The Man Who Colors Stars" is a video showcasing the impressive blend of photography and science that amateur astronomer and artist David Malin has created based on his work at the Anglo-Australian telescope. (See Resource List for details.) Another person who contributes simultaneously to art and science is William Hartmann. A well-respected astrophysicist, he has merged his science expertise with his artistic skill, and produces scientifically correct space art. Dana Berry is a graphic artist for the Wright Center for Science Education at Tufts University. Dana uses his artistic talent to explain and illustrate the world of science. He now produces science animations for *Nova, Discovery*, planetariums, and the Jet Propulsion Lab in California. Fred Hoyle is an astronomer who writes science fiction. Isaac Asimov, a hugely popular science fiction writer, had a degree in chemistry and wrote textbooks for chemistry, physics, astronomy, and biology. There are dozens of examples of people using their scientific knowledge to create and enhance art, and their artistic ability to portray science.

RESOURCE

Chapter 3: Familiarizing Yourself With the Night Sky

The Ishango Bone, thought to be a 20,000 year old lunar calendar

Introduction

People of ancient cultures viewed the sky as the inaccessible home of the gods. They observed the daily motion of the stars, and grouped them into patterns and images. They assigned stories to the stars, relating to themselves and their gods. They believed that human events and cycles were part of larger cosmic events and cycles. The night sky was part of the cycle. The steady progression of star patterns across the sky was related to the ebb and flow of the seasons, the cyclical migration of herds and hibernation of bears, the correct times to plant or harvest crops. Everywhere on Earth people watched and recorded this orderly and majestic celestial procession with writings and paintings, rock art, and rock and stone monuments or alignments.

When the Great Pyramid in Egypt was constructed around 2650 BC, two shafts were built into it at an angle, running from the outside into the interior of the pyramid. The shafts coincide with the North-South passage of two stars important to the Egyptians: Thuban, the star closest to the North Pole at that time, and one of the stars of Orion's belt. Orion was associated with Osiris, one of the Egyptian gods of the underworld.

The Bighorn Medicine Wheel in Wyoming, built by Plains Indians, consists of rocks in the shape of a large circle, with lines radiating from a central hub like the spokes of a bicycle wheel. Piles of rocks, called cairns, are located in the hub of the wheel and in several locations around the outside edge. Lines drawn between pairs of cairns point to the directions of the *heliacal risings* (the rising of objects just before the Sun, therefore visible in the early morning) of the stars Aldebaran, Rigel, and Sirius.

The Samoans used the stars to steer their canoes by aligning the head and tail of a canoe with two stars low on the horizon. The tail of Scorpio was a common star pattern against which to orient a canoe. They navigated from the island of Nokunono to the island of Atafu, beginning their voyage with Scorpio and continuing by steering directly towards the belt of Orion. For early navigators, the regularly changing patterns of the stars in the sky were a reassuring and unfailing guide.

Egyptian Sun Worship

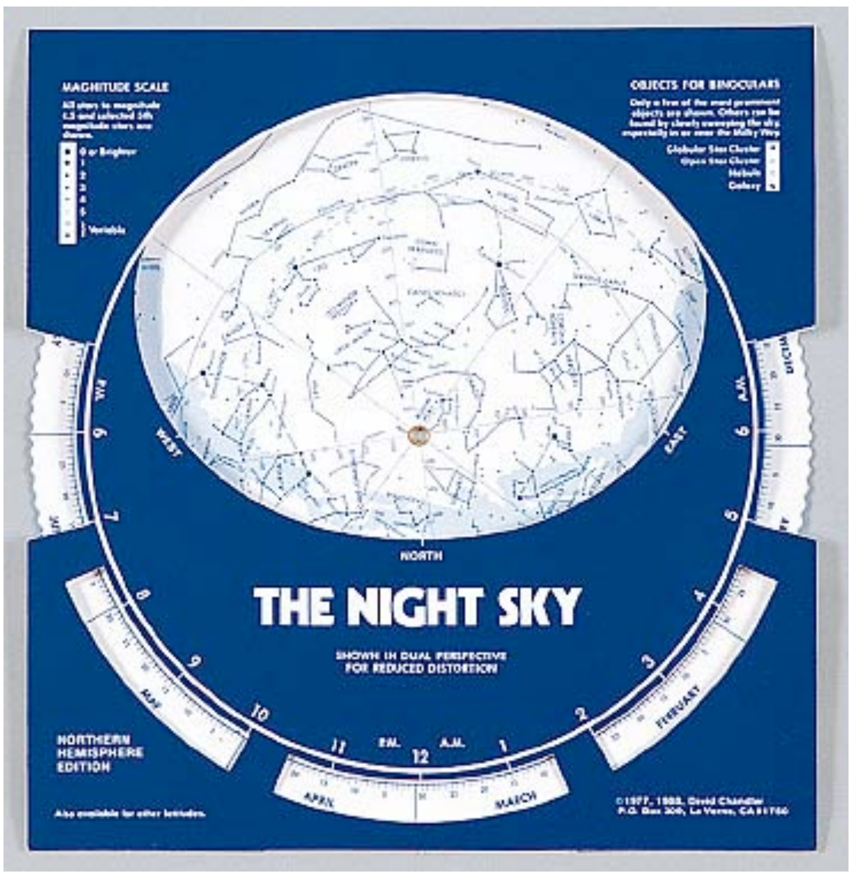
Today, familiarity with the night sky and the ability to locate its various objects and features is a necessity for those working in many branches of astronomy, such as solar and lunar astronomers, scientists studying planets, asteroids and meteorites, or those working at satellite-based observatories, and astronomers concerned with *astrometry*—the measurement of the distances and positions of stars. The following activities will help you develop your skills in locating stars and constellations, as well as tracking their motions across the sky. If you are just becoming acquainted with the night sky, the most appropriate instrument to use is your unaided eye. Later on, binoculars will aid you in locating dimmer objects. Small hand-held rotating star maps called planispheres and the *Sky-Gazer's Almanac* are useful aids, both for determining what is in the sky for any particular day and time, and for selecting the best times for viewing specific objects. These astronomical tools help you keep track of celestial motions during the course of the year—the stars and constellations that appear to gradually move across your field of view, and the planets that wander into and out of the night sky.

Investigation 3.1: Drawing a Star Map

Determine your best location from which to observe the night sky. After the skies are dark enough to see several stars and constellations, draw a picture of some part of the sky of your choice. Draw appropriately-sized points to denote the magnitudes of the stars. If you see patterns that you think may be constellations, draw in the lines where you think they belong. Represent the sky as accurately as possible, including the color of any stars you may notice. If you do not know any directions, then draw in one or more objects on the horizon to use as reference points. Do you think your classmates will recognize your star map? If you go out with your sky map at the same time of night one week later, would you expect to see the same patterns? Will they be in the same location? Try it and see. Record any differences on your map. Discuss your observations and results with your classmates.

Core Activity 3.2: Using the Planisphere

The *planisphere* is the modern-day amateur observer's star and constellation finding tool. It is a map of the stars with correct illustrations of the night sky for any particular day of the year. The star map is viewed through an elliptical opening, called the *horizon window*. Stars that are not visible for a particular day and time are hidden by the face of the star finder. Around the outside of the star wheel is a calendar of months and days which can be aligned with the hour markings on the frame. Note that the star map includes *constellations* and star magnitudes. Ready-made versions also include the names of major stars and deep-sky objects such as globular clusters, nebulae, and galaxies, along with the river of stars representing the disk of the Milky Way Galaxy, and the equatorial coordinate system. (You will learn about this system in the following chapter.) The Sun, Moon, and planets change their apparent position among the stars from year to year, so they are not located on the planisphere.



After you have either constructed your own planisphere or been given a ready-made version, set the planisphere to show tonight's sky at 9:00 PM, and rotate the wheel so that today's date, at the edge of the wheel, lines up with the 9:00 PM mark on the frame. Locate the stars and constellations that will be on your *meridian*. The meridian is an imaginary line across the sky from North to South that passes directly over your head.

The ready-made version will allow you to determine what star or constellation is at your *zenith*, which is the point on the meridian directly over your head. Note that *Polaris*, the North Star, is in the center of the planisphere and does not appear to move in the night sky. Now set the planisphere for 12:00 midnight tonight. Notice the apparent motion of the stars.

Now set the planisphere back to 9:00 PM. You are now ready to answer the following questions:

1. What constellation(s) are on your meridian at this time? (9:00 PM)

2. If you are using the ready-made planisphere, what constellation is nearest the zenith at this time?

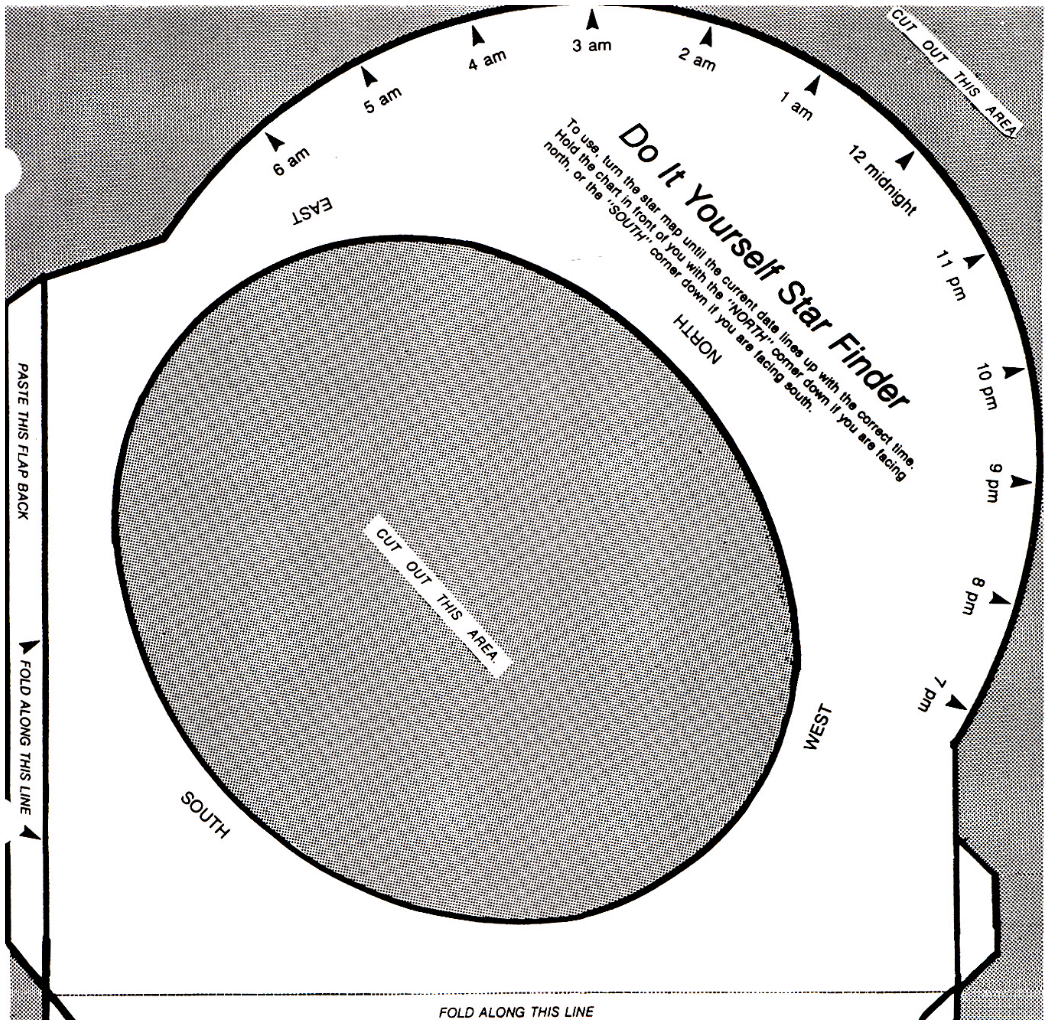
3. As with most star maps, the brightest stars are indicated by larger points. Locate five bright stars in tonight's sky and write down their names (if you know them or if they are on your planisphere), along with the names of the constellations to which they belong.

4. Prominent patterns of several bright stars, called asterisms, are indicated on the planisphere. Reproduce four asterisms as accurately as is reasonable. Label each, including the names of their brightest stars (if they are on your planisphere or if you know them).

5. Set the planisphere for 12:00 midnight. Locate one of the constellations that was on your meridian at 9:00 PM. Which way did it move? East or West?

6. What causes this apparent motion of the stars in the real sky?

You may wish to practice with other dates and times to become acquainted with your new tool for learning the night sky.



The *'Do It Yourself Star Finder'* was designed by Edna De Vore as an adaptation of the *'Sky Challenger'* by Budd Wentz of Lawrence Hall of Science. For information contact:

Edna De Vore
Independence Planetarium
1776 Educational Park Drive
San Jose, CA 95133

Lawrence Hall of Science
Astronomy Education Department
U.C. Berkeley
Berkeley, CA 94720

CONSTRUCTING AND USING THE PLANISPHERE

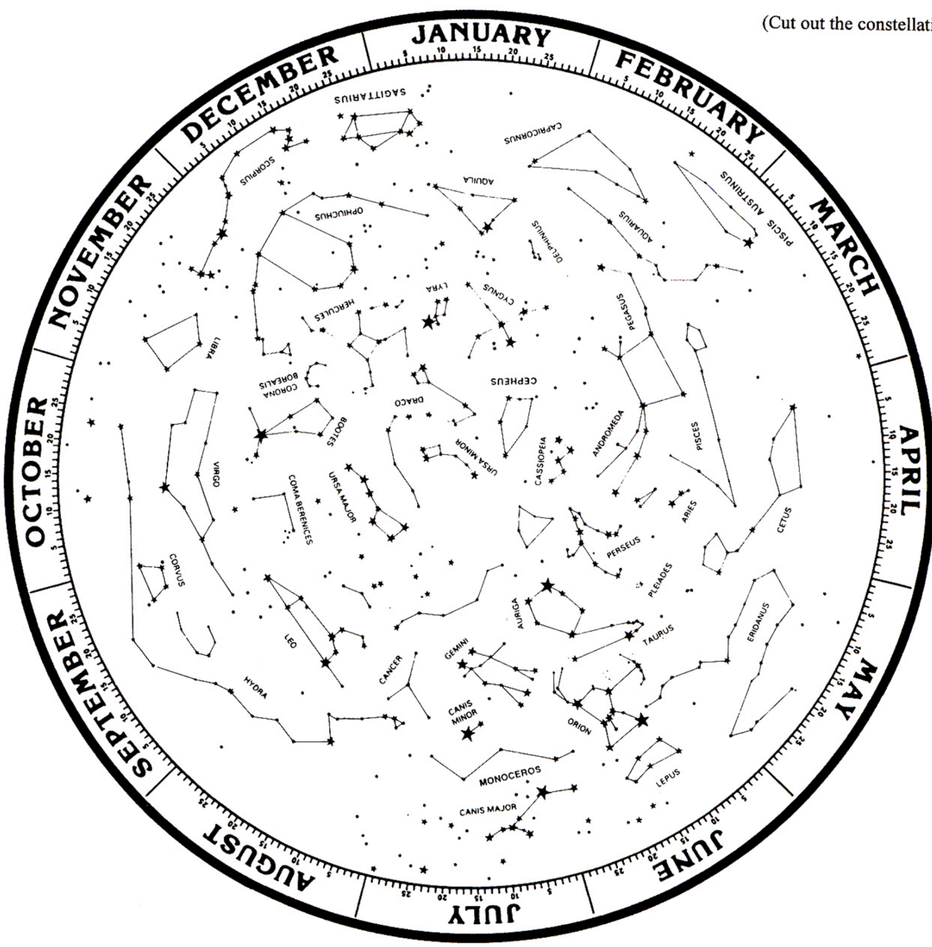
1. Cut out the templates for the sky constellation chart and the sky chart holder and glue to a piece of manila file folder. Insert the sky chart into the sky chart holder. Place a small clasp fastened through Polaris. Set the sky chart to 9:00 PM for today's date. The constellations which show are the ones which will appear in the sky tonight for northern latitudes of approximately 30-40 degrees.

2. Note that the North, South, East, and West horizons are labeled on the sky chart. Turn the sky chart to each direction to determine which part of the sky the constellations occupy.

Courtesy Lawrence Hall of Science

Sky Constellation Chart Template for Planisphere

(Cut out the constellation circle.)



Extension

The Sun, Moon, and planets are objects that change their apparent position among the stars, so they are not located on the planisphere. Over the course of the year, the Sun completes one circuit through the stars, following an imaginary path through the zodiacal constellations. That path is called the *ecliptic*. If we are given the constellation in which such an object is located at any given time, we can approximate its location on the planisphere wheel. Following is a list of the constellations and the dates where the Sun may be found. Locate the approximate position of the Sun on the wheel for today's date.

January 20–February 18	Capricornus
February 19–March 20	Aquarius
March 21–April 19	Pisces
April 20–May 20	Aries
May 21–June 20	Taurus
June 21–July 22	Gemini
July 23–August 22	Cancer
August 23 - September 22	Leo
September 23–October 22	Virgo
October 23–November 21	Libra
November 22–December 21	Scorpius
December 22–January 19	Sagittarius

7. Place a marker dot on the ecliptic at the approximate location of the Sun today. What actually causes the Sun to appear to move along the ecliptic through the stars? NOTE: See table above for the constellation in which the Sun is located for today's date.

8. Move the star wheel to place the Sun on the eastern horizon. You can now read the sunrise time for today by locating the date on the wheel edge, and reading the time that corresponds to that date. You have set the wheel to show the sky at sunrise. What time does the Sun rise?

9. Does the Sun rise exactly in the East? If not, then in what direction does it rise?

10. In what part of the sky would you expect to find the planets? Why?

Activity 3.3: Searching for Constellations

Now that you have become acquainted with the planisphere, you are ready to begin to know the night sky. Some initial planning will increase the success of your new adventure. IMPORTANT: Make sure your observing site and conditions are safe (refer to(f) and (h) below.)

1. Initial preparation

    a. Knowing the latest weather forecast, choose a night for observing and dress appropriately.

    b. Using your planisphere, determine what constellations will be up for the date and time you have elected to observe.

    c. Bring a flashlight and tape a piece of red cellophane over the light. (Some flashlights have a red light attachment on one end.) This will allow you to read your planisphere or charts, and write without interfering with the adaptation of your eyes to the dark.

    d. Use a compass if you are not sure of the cardinal directions—North, South, East, and West—at your location.

    e. Have a pencil and a notebook to record your observations and any special events or questions you may want to remember. Drawing a picture of the sky is helpful. Always record the date, time, and weather conditions.

    f. Choose a viewing site that is safe, and that has the least obstruction from buildings and trees. If you are on someone else's property, be sure you have permission to be there. Find a comfortable surface—you may want to bring a lounge chair or blanket. Looking up at the night sky for long periods of time while standing or sitting is uncomfortable.

    g. Something to eat and/or drink is not essential, but will certainly make your experience more enjoyable.

    h. Do not observe alone. Bring someone with you—parents, friends, maybe an amateur astronomer. Any knowledgeable person with a love for the night sky will eagerly accompany you to share their enthusiasm. You are now ready to begin.

2. Find your bearings with the compass or map, and make sure you are facing one of the cardinal directions.

3. Hold the star chart or planisphere straight in front of you so that the direction of the sky you are facing is at the bottom of the chart. Now raise your arms and hold the chart directly above your head so that when you look straight up, you are looking at the chart. North on the chart should be in the direction North, East on the chart to the East. The sky and your planisphere or chart should now have the same orientation. Hold the planisphere up long enough to get a general idea about how to match the sky with the chart.

4. Finding North and the Pole Star:

   The Big Dipper (an asterism in the constellation Ursa Major, or Big Bear) is visible throughout the year if you have a clear horizon and your latitude is greater than 30 degrees. First spot the dipper; then draw an imaginary line between the two stars at the end of the bowl farthest from the handle (called the pointer stars). Extend this line about 5 times (see Figure 3.3); the line will hit the bright star Polaris (the North Star or Pole Star). Although Polaris is not one of the brightest stars in the night sky, it is still brighter than the stars surrounding it, and the shape of its asterism, the Little Dipper (in the constellation Ursa Minor, or Little Bear), is fairly easy to see.

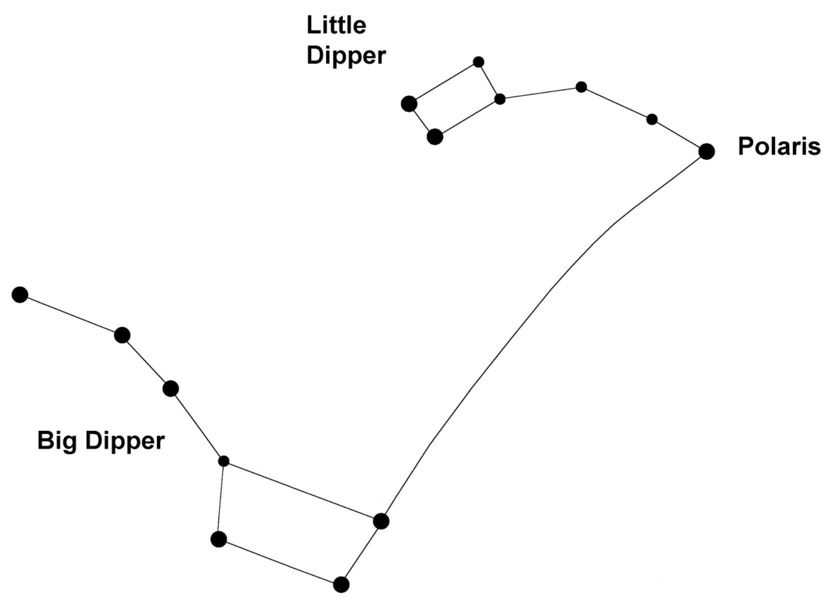


Fig. 3.3

   Polaris lies almost exactly above the Earth's geographical North Pole, and is the point around which the whole sky appears to be turning.

5. Spring and Summer: The Big Dipper's handle is a curved line. From February to August, by extending the arc, you can follow the "Arc to Arcturus," the brightest star in the constellation Boötes the Herdsman (see Figure 3.4). Note the reddish-orange color of Arcturus.

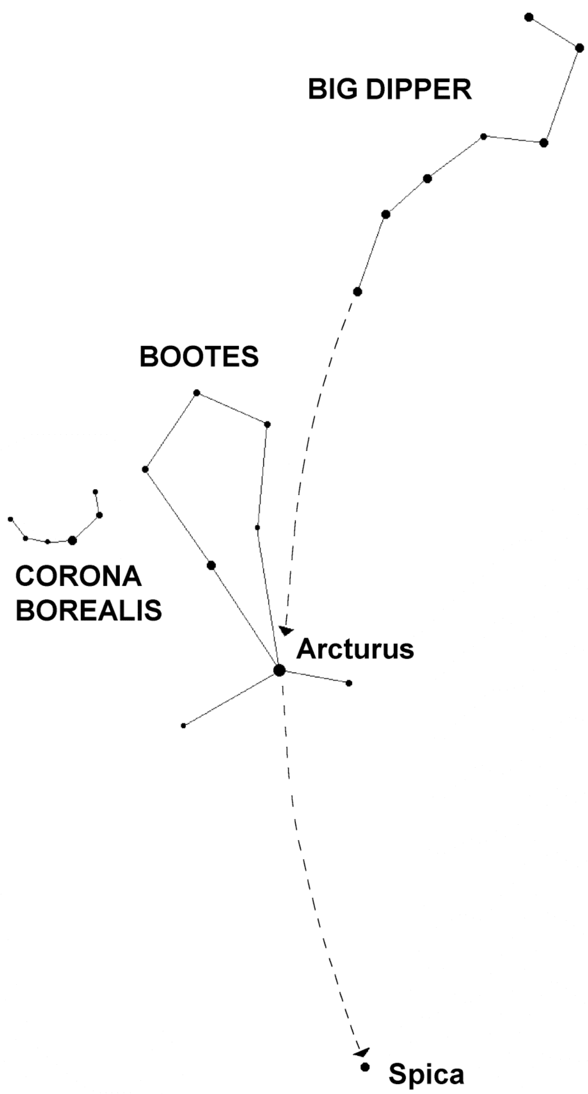


Fig. 3.4

Just to the east of Boötes is the Northern Crown (Corona Borealis), which looks like a crown to some and a horseshoe to others. Extend the arc from Arcturus and you will see the bright bluish star Spica, the brightest star in the constellation Virgo.

To observe Regulus, the brightest star in the constellation Leo the Lion, go out when the Big Dipper is high in the sky. Use the two stars next to the handle and draw a straight line towards the Southwest. It will first hit the star in the upside down lion's shoulder and then Regulus. It is also the bottom star of the sickle, which is the most recognizable part of the lion (see Figure 3.5).

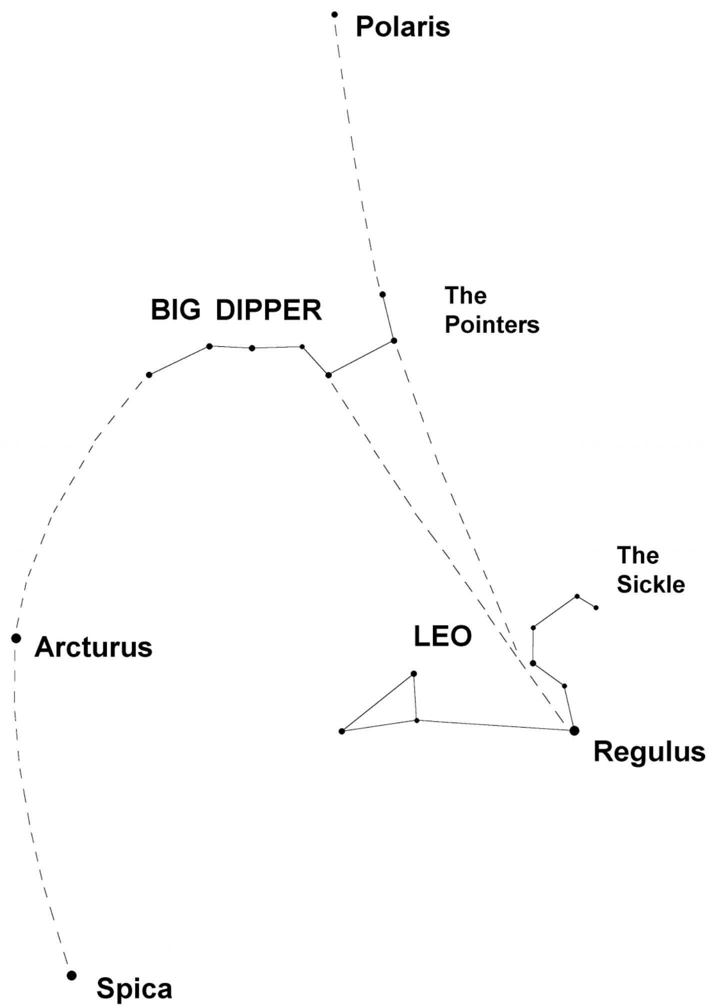


Fig. 3.5

6. Summer: Join the two inner stars of the bowl of the dipper with a line which you will continue to follow northward. Eventually, this line will come to an area dominated by three bright stars: Vega in Lyra the Harp, Deneb in Cygnus the Swan, and Altair in Aquila the Eagle. This area is spread over a large section of the sky and these three stars form the Summer Triangle, a large V-shape in the sky. Vega is the brightest apparent magnitude star in the summer sky (see Figure 3.6).

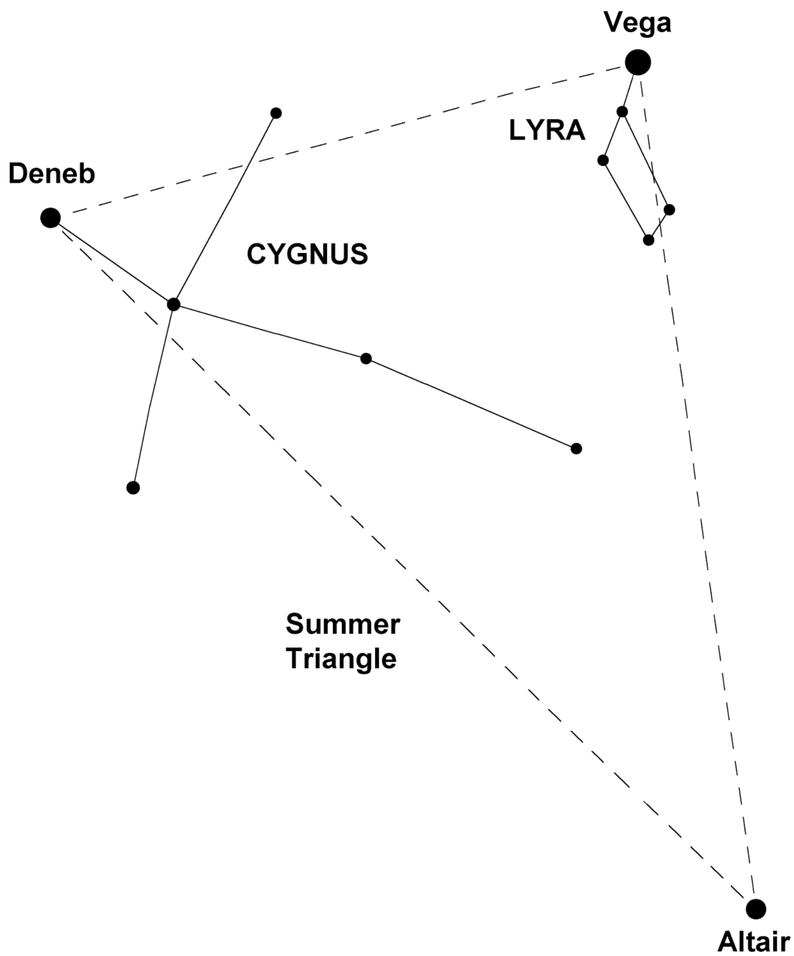


Fig. 3.6

7. Winter: High in the southern sky is Orion the Hunter. The three belt stars in a straight line are the first stars you will see. Orion's upper left corner is marked by the red star Betelgeuse, and its lower right by the brilliant bluish star, Rigel (see Figure 3.7). Trailing along below Orion (extending the belt stars southeast) is Canis Major (Big Dog), one of Orion's hunting dog companions. This constellation contains Sirius, the "Dog Star." Sirius is the brightest apparent magnitude star in the winter sky. The three stars Procyon, Sirius, and Betelgeuse form the asterism for the Winter Triangle. Extend the line joining the belt stars northwest about five times and you encounter the orange-colored star Aldebaran in the constellation of Taurus the Bull. Aldebaran separates Orion from the small cluster of stars known as the Pleiades.

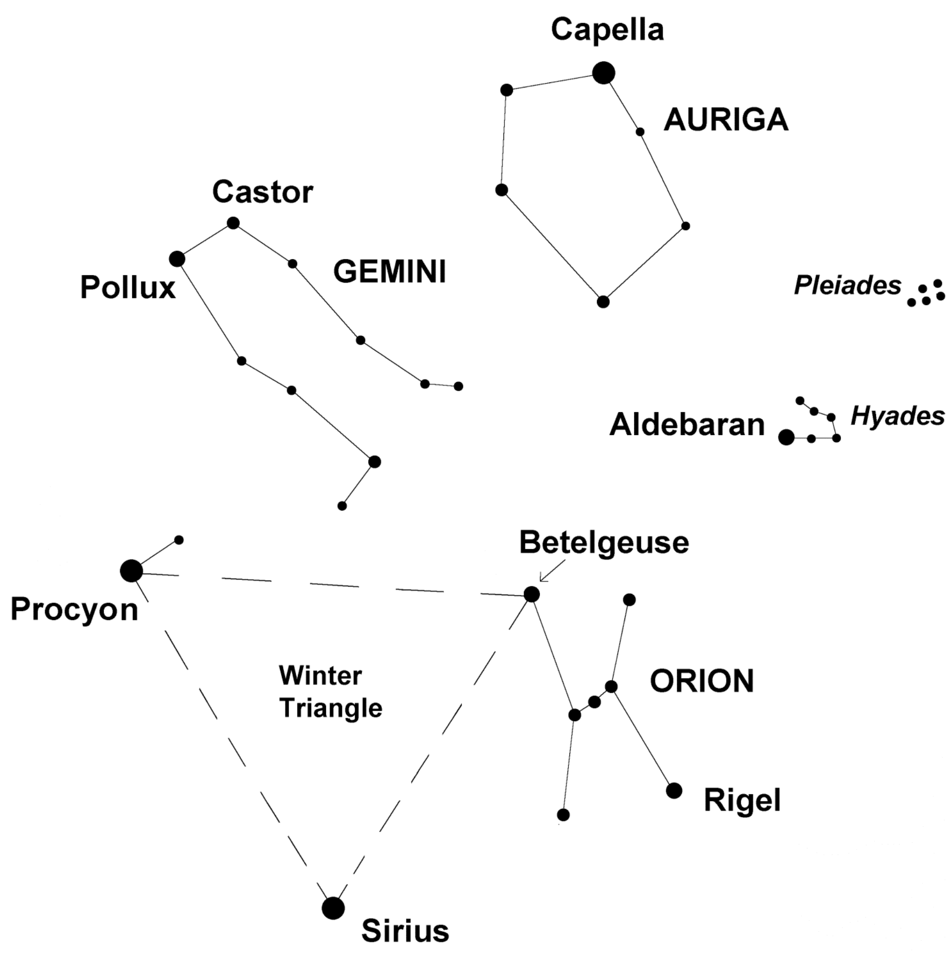
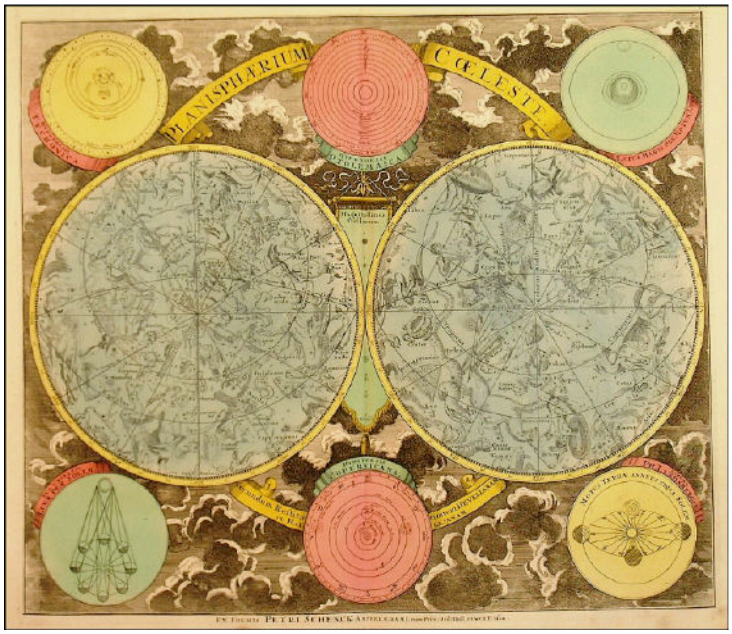


Fig. 3.7

This activity was a very brief introduction to the night sky. You will learn how to make your own shortcuts to the various stars and constellations once you become expert in reading your planisphere or star chart. Watch for the different colors of the stars. Later on you may decide to learn how to locate nebulae, globular clusters, and the Andromeda Galaxy.



Planisphaerium Coeleste, Pieter Schenk, 1705

Where to go, what to do....

What would you do if you and your family and friends lived on an island about 2,500 years ago, and there was nothing but water as far as you could see? Let's say you and your friends were pretty good with boats. You can build big sailing boats, and you've already made lots of trips around the island in all kinds of weather. You don't have much else to do, but you do pay attention to the weather every day, and you have been watching the skies day and night for several years.

After a while, you begin to notice that there are patterns in the way the Sun appears in the morning and goes away in the evening, and you notice a similar motion in the stars at night. There are some stars that always appear at nearly the same point on the horizon every night where the Sun appears during the day, no matter what month it is, and those stars go away each night on the opposite horizon.

You notice that there are other stars which rise and set in other directions, and that these stars will rise and set in the same places only once each year.

You notice, too, that most of the time the wind comes from the direction that the Sun rises in the morning, and blows towards the direction where the Sun sets in the evening. You also notice that the waves in the sea also move in the same direction as the wind most of the time, and that even when the wind dies down, the large waves continue to move in the same direction.

Once you get a feel for the Sun, stars, wind, waves, and the time it takes for these things to repeat themselves, you get the idea that you might be able to sail your boat for longer distances. You wouldn't have to keep your island in sight anymore, because you could keep the Sun and stars in view instead, and you could keep an eye on the direction the waves were moving in as well. You could sail off in any direction and return to your home island again as long as you paid attention to which way you were sailing in relation to the Sun, stars, wind, and waves.

Every time you returned home from another sail out of sight of land, you became more confident of your ability to navigate by the Sun and stars. Maybe it would be a good idea to head straight for the direction where the Sun, stars, wind, and waves all seem to be coming from. That way, you would be sure of your direction all the time, whether coming or going, and also, you could sail as far into the wind as possible until your food and water ran low, and then turn around and have the wind blow you safely back to your home island.

In time, you or your friends would find other islands out there. In a few generations, your people would be able to travel even farther by establishing new home islands farther out each time, and using the new home island as a starting point to explore more of the ocean in every direction.

Many believe that the Polynesians traveled to, and settled, the hundreds of islands of the western Pacific ocean over several hundred years by learning how to navigate through such simple beginning observations as outlined here. In time, they would have refined this basic knowledge into a more complex skill. Archeological evidence shows that the Polynesians generally moved from west to east as they expanded their exploration and colonization of other islands. The Tonga islands were occupied about 500 BC, and the island of Tahiti, 1,400 miles to the east, was occupied 700 years later. Altogether, the Polynesian people travelled over a triangular area of the Pacific that is about 4,000 miles on each side. Some of the islands in this area are up to 1,000 miles away from any neighboring islands. It would be very difficult and dangerous just to blindly sail off in any direction and hope to find land somewhere without a reliable navigational system based on observation of the stars. It would be even more difficult, if not impossible, to return home to tell about what you had found.

Sometimes the astronomical knowledge gained from sky gazing was learned only for its practical value. Early Polynesian navigators memorized long sequences of rising and setting stars which could be seen, one after the other, above the same spot on the horizon. They rarely used charts, although they sometimes constructed compasses out of sticks to symbolize the patterns of currents and swells they would encounter on their voyages from island to island.

Before the American Civil War, slaves escaping via the Underground Railroad also looked to the sky for direction. Their compass was even more simple and more portable than the Polynesians' stick compass: it was a song. A song called "Follow the Drinking Gourd" was actually a secret code describing a sky and land map directing the slaves towards freedom in the North. The slaves had to conceal their knowledge of observational astronomy, especially of the northern sky. Songs are an integral part of African culture; the slaves had a long heritage of transmitting information through songs. Creating "Follow the Drinking Gourd" not only strengthened traditional customs among the slaves, it also established a spiritual bond among them as a symbol of freedom from the suffocating chains of slavery.

The song instructs the slaves to leave in winter and travel north along the Tombigee River to the Tennessee River and across the Ohio River. The "drinking gourd" refers to the Big Dipper, easier to see than the fainter Little Dipper and dim Polaris. The slaves kept their eyes on the bright stars of the drinking gourd as they journeyed through the dark and heavily wooded terrain towards the Underground Railroad and liberty.

Follow the Drinking Gourd

When the Sun comes back
And the first quail calls
Follow the Drinking Gourd.
For the old man is a-waiting for to carry you to freedom
If you follow the Drinking Gourd.

The riverbank makes a very good road.
The dead trees will show you the way.
Left foot, peg foot, traveling on,
Follow the Drinking Gourd.

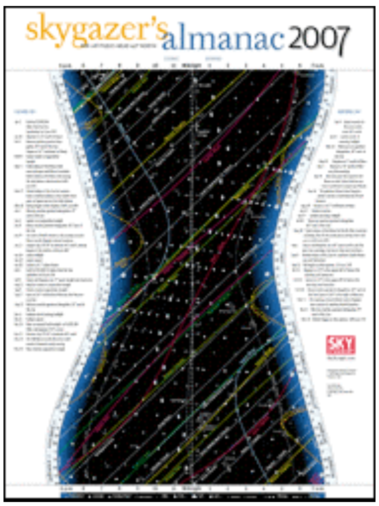
The river ends between two hills
Follow the Drinking Gourd.
There's another river on the other side
Follow the Drinking Gourd.

When the great big river meets the little river
Follow the Drinking Gourd.
For the old man is a-waiting for to carry you to freedom
If you follow the Drinking Gourd.

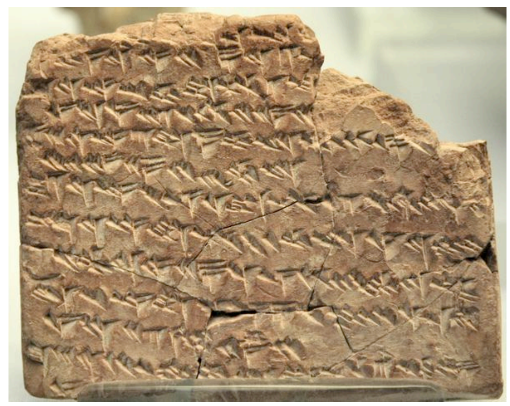
Follow the Drinking Gourd, follow the Drinking Gourd
For the old man is a-waiting for to carry you to freedom
If you follow the Drinking Gourd.

Activity 3.4: Using the *Sky-Gazer's Almanac*

Another useful astronomical tool is the *Sky-Gazer's Almanac* (SGA). The planisphere tells you what constellations are visible for a specific day and time. The SGA tells you the times of sunrise and sunset, moonrise and moonset, and tells you the lunar phases. It is a graph of all astronomical events in the night sky for every day of the year, and gives the times of these events. It includes the rise and set dates for seven of the planets. If, for instance, you wanted to see Venus at its closest approach to Earth, the SGA would tell you the day and time to observe.



Stargazer's Almanac



Ancient Babylonian almanac describing positions of planets

Dates on the SGA run vertically, from top to bottom. Time of night runs horizontally, from sunset at left to sunrise at right. To read the chart, find the date that you want to observe and read across to find the times of different events. Your skill at this will improve with practice. Pick a date, for instance, April 7, and follow the events of that one night. Follow the fine string of dots across the graph. Each of these dotted lines represents an evening—for example, a Sunday night to a Monday morning—and the individual dots are spaced five minutes apart. Every half hour there is a vertical string of dots that runs up and down the chart. On the vertical dotted lines, one dot is the same as one day. Looking across the SGA with a sweep of the eye, we can see that throughout the course of the evening there are many "event lines" that tell us exactly when something is going to happen. And along with these, on the edges of the chart, there is information about some of the major astronomical events. The back of the SGA gives further details on how to decipher the chart. One more term necessary to understand is *transit*, which is the passage of a celestial body across an observer's meridian.

In order to obtain an accurate time for the events on the chart, it is necessary to make two calculations. The first one is easy. If it is Daylight Savings Time, then one hour has to be added to the times on the chart. The second calculation is more involved. The times given on the chart are *local mean time* (LMT). Local mean time is not the same as the time on your watch, unless you are located on the line of longitude on which your time zone is centered. In North America, Eastern time is standardized to 75° longitude, Central to 90°, Mountain to 105°, and Pacific to 120°. If you are on or close to one of these lines of longitude, no correction has to be made. Otherwise, you will have to make a correction. To make a correction, besides knowing what time zone you are in, you need to determine the closest line of longitude for your location. After obtaining times from the chart, you need to add four minutes for each degree of longitude that you are west of your time zone center, or if you are east of the time zone, subtract four minutes for each degree. For example, if you live in Boston, Massachusetts, you are located at 71° longitude or 4 degrees east of 75° longitude (the center of the Eastern Time Zone) and need to subtract 4 minutes for each of the 4 degrees, for a total of 16 minutes. Therefore during Standard Time you will always subtract 16 minutes from the times on the SGA to get the correct times for events. During Daylight Savings Time, you will add 44 minutes (add one hour for Daylight Savings and subtract 16 minutes for the time zone correction). The corrections for several major cities are listed on the back of the Almanac.

EXAMPLE: Using the SGA in Boston, Massachusetts, located at 71° longitude in the Eastern Time Zone, during the month of August at 9:00 PM:

1. Daylight Savings Time is in effect, so add one hour to convert this Standard Time in the SGA to Daylight Savings Time: 9:00 PM + 1 hour = 10:00 PM;
2. Eastern Time is centered at 75° longitude. Boston, at 71° longitude, is 4° East of the center of the time zone.
3. 4 minutes for each degree x 4 degrees (4 min/° x 4°) = 16 minutes;
4. Subtract 16 minutes for being 4° east of 75° longitude: 10:00 PM – 16 minutes = 9:44 PM

Therefore, a viewing time of 9:00 PM on the SGA actually occurs at 9:44 PM in Boston during Daylight Savings Time, and 8:44 during Standard Time (9:00 – 16 minutes).

The following activities will familiarize you with the information available on the *Sky-Gazer's Almanac*. Remember there is also information listing events on both sides of the graph.

THE SUN

Notice the sunrise line and the sunset line.

1. Would you have to correct for Daylight Saving Time if you were observing tonight? ____
2. What is the time correction for your location? ______________________
3. On what side of the page is sunrise?_____________________________
4. At this time, where in the sky will the Sun be in general? ________________
5. What is the time of sunrise on March 22nd? _________________________
6. What is the time of sunset on September 27th? ______________________
7. On what day in December is the duration of night the longest?____________
8. How long is the night on this day? ______________________________
9. On what date is the duration of daylight longest in the Northern Hemisphere? ____
10. How long is the night on this particular day (in question 9)? _____________
11. Why is the chart shaped like an hourglass? _________________________

THE STARS

Listed on the Almanac are diagonal bright white lines designating the rise or transit times for several bright stars and a few larger celestial objects.

1. When an astronomical object is transiting, where does it lie in the sky? Why?

   ____
2. On what date will the Orion Nebula (sometimes referred to as Messier 42 or M42) transit near midnight? ____
3. What time does Deneb transit on August 15th? _______________________
4. Why are all the transit lines for stars straight and parallel? _______________

THE MOON

There are Moon symbols designating the phase of the Moon and its rising or setting time for each day of the year.

1. At what time is Moonrise on March 21st? ________________________________
2. On what day and at what time does a full Moon rise in the month of September?____
3. The transit lines for some of the bright stars "touch" or intersect some of the Moonrise or set symbols. At what time and date in January does a setting Moon intersect the Sirius transit line?____
4. Does this intersection mean that the Moon and Sirius will appear very near to each other in the sky on that date? Explain ______________________________
____
5. When you want to observe a very faint object, such as the Orion Nebula (M42), you want the sky to be dark. Thus, you would like a moonless night, a night in which the Moon sets early, or a night in which the Moon rises late. If you wanted to see the Orion Nebula with a moonless sky, when would you look? Give at least 2 dates that differ by at least seven days. (The Orion Nebula is in the constellation Orion. Use your planisphere to determine its location in the sky.) ______________
____

THE PLANETS

Seven of the nine planets are represented on the SGA. The rise, transit, and set lines of these planets are in different colors. Each planet has its own unique color.

1. When is (are) the "best" time(s) to observe Mercury, and where in the sky would you look? ____
2. On what date is Venus at greatest brilliance?______________________________
3. On what date(s) does Jupiter set at midnight? ______________________________
4. If you wanted to see the greatest number of planets in one night, what night would it be and what planets could you observe? Discuss why you chose that night. ____
____
5. Study the transit lines for all the planets. Some are straight and parallel like those of the stars, and others are curved. Why?_________________________________

METEOR SHOWERS

There are several meteor showers indicated on the SGA.

1. Which ones occur during this season? ___________________________________

2. The best conditions for viewing a meteor shower occur on a moonless night. Of the meteor showers for this season, which one occurs under the best conditions? Explain. ____
____

SPACK TALK

The seemingly simplistic astronomical observational tools that you have used to observe and determine the motions of the Moon, stars, and planets would have appeared extremely sophisticated to the Pawnee Indians living on the Great Plains of Nebraska a century ago. They were skillful sky watchers. Proof of their observational activities resides in the Pawnee collection of the Chicago Field Museum of Natural History. Discovered in one of the Pawnee "Sacred Bundles"—groups of ceremonial objects wrapped together—was a **star chart** (see Figure 3.8). The chart is made from a piece of tanned elk skin, oval in shape, and approximately 38 cm by 55 cm in size. Its exact age is uncertain, but it is thought to be between 100 and 300 years old.

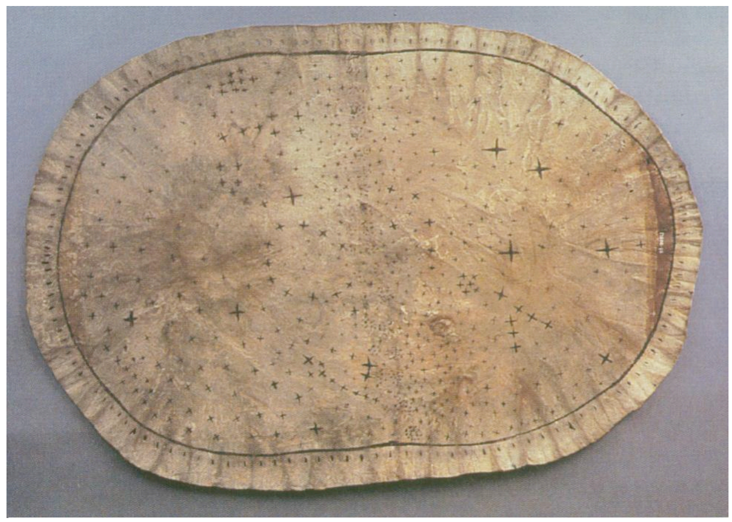


Fig. 3.8

One end of the Pawnee sky map is colored reddish-brown and the other brownish-yellow. The stars are represented by a four-pointed figure and drawn in five different sizes, representing different magnitudes. The map depicts several **constellations** with the most prominent stars drawn according to brightness or magnitude. **Polaris** is shown at a brighter magnitude and all the remaining stars in Ursa Minor are depicted as having a similar, fainter magnitude. Through the center of the map is a stream of fainter magnitudes, representing the stars of the Milky Way as they appear to the naked eye. The Milky Way appears in the center of the chart, and it seems to be representing a division between the two major seasons. The star groups to the right of the Milky Way resemble the summer night sky and end with the band of brownish-yellow; the star groups to the left resemble the winter night sky and end with the reddish-brown band of color. A solid line around the oval represents the **horizon**. The Pawnee constructed this portable **planisphere** to keep a record of the nighttime sky.

Some of the **asterisms** for the constellations that seem to be represented on the sky map are outlined in Figure 3.9. The constellations are Taurus (including the open cluster,the Pleiades), Orion, Auriga, Lyra, Corona Borealis, Ursa Minor, and Ursa Major. There has been more than one interpretation of these constellations. Some of the positions of the constellations do not coincide with their real sky counterparts—although perhaps we simply do not know how to interpret the chart. There may be other aspects of the sky being represented, such as important constellations moving from the horizon and overhead past the **meridian** and/or **zenith**. The stars and constellations the Pawnee considered more significant in tracking the seasons may be exaggerated, and the remaining stars made less prominent in the background, producing distortions in scale.

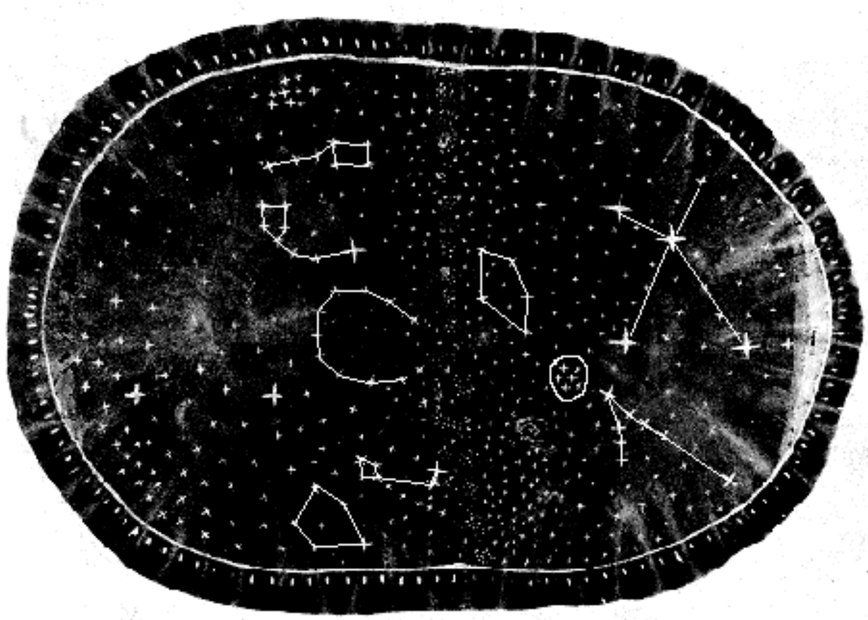
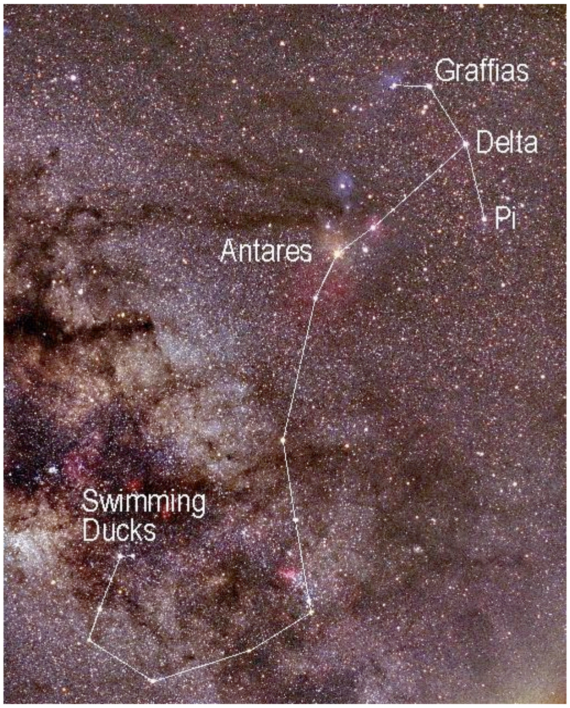


Fig. 3.9

The importance of the sky chart to their culture was considerable, important enough to be included in a sacred bundle. Every Pawnee household had a sacred bundle, which they believed were gifts from the stars, whom they considered to be supernatural beings that often descended to Earth to maintain relationships with mortal people. One major Pawnee legend deals with the origin of the sacred tribal bundle, which was guarded and protected by the tribal shaman for its magical charms. The bundle could be used to invoke the aid of the Great Spirit in bringing buffalo to the tribe in times of hunger.

The Pawnee Indian sky map gives no indication of the importance of the Sun's apparent yearly path through the sky, called the **ecliptic**, or the day of the year when the Sun reaches its highest point in the sky—the summer **solstice**. They did not develop an accurate lunar calendar either. Most ancient cultures, as well as other North American Indian tribes, had calendars calculated with either the Moon or the summer solstice, but the Pawnee were the star people of the Plains. The Pawnee marked their year, not with the Sun's motions or the phases of the Moon, but with the appearance in the southeast sky of two small stars known as the "swimming ducks," and the Pleiades. The stars served not only as a calendar for the Pawnee—they developed more elaborate star ceremonies and rituals than any other tribe. The stars and constellations were a great influence in almost every aspect of their lives, and even their houses were laid out in patterns which duplicated the patterns of the constellations, indicating the positions of their most important star gods.



For the Pawnee, the arrival of spring marked the beginning of their year. Spring began with the appearance in the sky of two stars called The Swimming Ducks. These stars are Lambda and Upsilon Scorpii, the stinger in the tail of the scorpion. The appearance of the Swimming Ducks was the time for thunderstorms and the Thunder ritual. To the right of the Swimming Ducks, the curving line of stars that comprise the Scorpion's body was seen as a separate constellation representing a snake, ending with the red star Antares the head of the snake.

Pawnee Spring

Unit 2: INTRODUCING THE SKY

Unit 2 prepares students for making visual observations. Going out and looking into the night sky will introduce students to the wonders of the universe from their own backyards. In Chapter 3, “Familiarizing Yourself With the Night Sky,” students will become acquainted with the constellations by constructing and using a simple astronomical tool, the planisphere. They will also learn how to obtain additional information by using the Sky Gazer’s Almanac. Chapter 4, “Our Bearings in the Sky,” helps explain the motions of objects across the sky by having students make and record observations using quadrants and shadow sticks. Students will learn about the celestial sphere, and use the equatorial coordinate system to plot constellations.

CONTENTS FOR UNIT 2

Poster Page: Astrology or Astronomy? (Horoscopes and Precession)
Space Talk on Lunar Libration

Relationship to National Science Standards and Benchmarks

This unit addresses three of the five unifying concepts and processes underlying the national science standards: the order and organization of the Solar System, constructing and explaining models, and understanding patterns of change by direct observation and measurement. The *History and Nature of Science* content standard states that 7th through 12th grade students should understand that diverse cultures have contributed to scientific knowledge and technological advances, and that the beliefs of each culture have added their own unique perspective to the scientific enterprise. Some of the simple astronomical tools used today have changed little since their conception, and the development of these tools was motivated by the desire to understand the natural world. Today, this is still the driving force for the development of increasingly sophisticated tools. Learning to see these historical connections between technology and the acquisition of knowledge supports the *Science and Technology* content standard. Investigations and activities that take place over long periods of time, take place outside of the classroom, and deal with real world conditions, emphasize and promote inquiry learning as set forth in the *Science as Inquiry* standard. During the inquiry process of observing and collecting data, students learn about the motions observed from Earth and the Earth's place within the Solar System, as stated in the *Physical Science* and *Earth and Space Science* content standards. This unit supports concepts from Benchmark's *Nature of Mathematics,* as students record data and transform it into graphs and tables to show relationships among different variables and to determine patterns.

Chapter 3: Familiarizing Yourself With the Night Sky

Summary

This chapter introduces you to techniques of sky observation and what you will see. It emphasizes how to use star charts to find your way around the sky by "star-hopping," and how to use planispheres to determine what constellations are in the sky for any particular date and time. The *Sky Gazer's Almanac* helps to determine such information as rise and set times for the Moon, and what planets will be in the sky for any day of the year.

Terminology

asterism	heliacal rising	meridian	solstice
astronometry	horizon	planisphere	star chart
constellation	horizon window	Polaris	transit
ecliptic	local mean time	*Sky-Gazer's Almanac*	zenith

Common Misconceptions

1. *Stars and constellations always travel directly from East to West.*
2. *The Sun rises due East and sets due West.*

SUGGESTIONS FOR THE POSTER PAGES, INVESTIGATIONS, AND ACTIVITIES

Investigation 3.1: Drawing a Star Map

The students do not need to know the names of any stars or constellations or any cardinal directions to do this activity. It will give them practice at observing and drawing the apparent magnitudes of stars in the real sky, and the opportunity to locate a good observation site for Core Activity 3.4: Searching For Constellations. If they draw their maps carefully with good reference points, they should be able to see the sky changes in their map within a week's time. Have the students exchange their maps with each other and try to match the drawing on the map with what they see in the sky. Earthbound reference points are vital (trees, buildings, and so on), and provide a good scale for the drawings. Students should give a magnitude key on the map to explain the sizes of their points. Exact magnitudes are not important, just what star is brighter and by how much. Later on in the chapter, you may have them compare their maps with other sky charts of the same parts of the sky. You may choose to have the students explain their charts to each other. It would be an excellent introduction on why it is important to have a coordinate system to locate objects in the sky. *Note:* Here we use the terms “map” and “chart” interchangeably, although the word “chart” is used more frequently in astronomy.

Core Activity 3.2: Using the Planisphere

Spend some time having your students become familiar with some simple astronomical tools to aid them in their observations. Included are activities involving the planisphere and the *Sky Gazer’s Almanac* (for more advanced students). For a helpful discussion on how to use the planisphere, show your students the section of the HOA video entitled “How to Observe Variable Stars.” If you have a nearby planetarium, the staff can usually provide programs to help students learn their way around the sky before actual observations are made. Have students keep an observational log, entering date, time, direction, and weather conditions, as well as drawing what they see. This is an excellent beginning exercise to learn the skill of data collection.

HOA VIDEO

The planisphere is a map of the stars with correct illustrations of the night sky for any particular date. The star map or star wheel is viewed through an elliptical opening called the *horizon window.* Around the outside of the star wheel is a calendar which can be aligned with the hour markings on the frame. Note that the star map on the make-it-yourself planisphere includes constellations and star magnitudes (the apparent brightness). The ready-made versions may also include the names of major stars, clusters, nebulae, galaxies, the Milky Way, the equatorial coordinate system of right ascension and declination, and the ecliptic. The Sun, Moon, and planets change their apparent position among the stars, so they are not located on the planisphere. Planets move along the ecliptic and look like very bright stars which are not marked on the chart. The *ecliptic* is the dashed line on the planisphere that marks the apparent path of the Sun, Moon, and planets in the sky.

You may choose to use a ready-made planisphere or have the students construct their own—a template is included in the student section. If you use the ready-made planisphere, the best source for them is given in the Resource List. Sky charts for any date and time can be obtained from several software packages, also listed in the Resource List. *(Note:* You can wait until the following chapter on celestial coordinates to introduce the students to the terms *right ascension, declination,* and *ecliptic*—they are not necessary to know for the activities within this chapter. You also can ignore the deep-sky objects and their celestial coordinates until the next chapter.)

RESOURCE

If you are not familiar with planispheres, the following instructions will be beneficial:

To set the planisphere to show tonight’s sky at 9:00 PM, rotate the wheel so that today’s date, at the edge of the wheel, lines up with the 9:00 PM mark on the frame.

Locate the stars and constellations that will be on your *meridian,* an imaginary line that runs from North to South directly over your head. With the ready-made version, it is easy to locate your *zenith,* the point directly overhead on your meridian, because the lines of latitude are labeled. For example, if you are at 35° latitude (called declination), your zenith is also at 35° latitude in the sky above. Note that Polaris, the North Star, is in the center of the planisphere (the gold circle or rivet on the ready-made version), but NOT at the center of the horizon window, and does not appear to move in the night sky. Now set the planisphere for 12:00 midnight tonight. Notice the apparent motion of the stars. The stars are not in fact moving; it is the rotation of the earth that makes the stars appear to have moved across the sky. You now know how to operate the planisphere. Make sure the students understand the terms *meridian, zenith,* and *horizon.*

Answers

1.–4. (The first four depend upon the season; the first two are also dependent upon the date selected.)

5. West

6. The northern hemisphere's counterclockwise rotation from West to East.

Extension

If using the ready-made planisphere and working with older students, the extension questions can be added to those above if you want to introduce the terms *ecliptic,* which is the apparent path of the Sun, and *zodiac,* which describes constellations along the ecliptic. For these questions, the students are provided with the dates that the Sun is occupying each zodiacal constellation. NOTE: These are the actual positions of the Sun at this time, not the incorrect positions which students associate with their horoscope.

Answers

7. The Earth's orbit around the Sun.

8. (Depends upon date)

9. In the summer the Sun rises North of East, during the winter it rises South of East.

10. Along the ecliptic.

Activity 3.3: Searching for Constellations

If students have not yet been introduced to nighttime observing, now is the time. It is essential to the variable star program, which is the heart and soul of this curriculum. Organizing nighttime observations can be difficult, especially with younger students. Keeping groups small, or having students work individually works better. Getting parents involved is also helpful, as they can organize small star parties in backyards and local parks. Sometimes local amateur astronomy clubs can be helpful, or science centers and museums. Whatever method works for you, getting students out and looking up is what makes astronomy fun. Just a few of the brightest stars and easiest constellations in the summer and the winter sky are included in this activity. Once you and your students have located a few constellations and have an idea of how they appear in the sky compared to how they look on the planisphere, it becomes easier to locate others. An excellent aid for learning the constellations is the game *Stellar 28,* which uses a board and cards both with and without the constellation lines drawn in. There is also a software version of this game. (See Resource List.) RESOURCE

Poster Page: Where to Go, What to Do... (Navigating by the Stars)

The *Follow the Drinking Gourd* song is one instance where practical observational astronomy transcended into the spiritual domain. The meaning of this song, which was actually a disguised sky and land map for escaping slaves heading north toward freedom, has only recently become known; there are probably other examples yet to be discovered. Conversely, there are many examples of astronomical phenomena which were initially considered only from a spiritual perspective, and then became a focus for practical applications. Celestial objects and events that were once worshiped or feared have become useful tools with which to gain knowledge of celestial motions and properties. Solar eclipses, thought at one time to be punishment from vengeful gods, are now used to study the chromosphere, an atmospheric layer of the Sun which becomes visible only during a total eclipse. Similarly, comets aroused great alarm in past times, but scientists now study them to discover indicators of the conditions present during the formation of the Solar System. Sirius, the bright star in Canis Major, was both venerated and dreaded by the Egyptians; eventually its appearance in the predawn sky became merely an indicator of when to plant crops along the Nile, and so a friendly reminder of spring.

Activity 3.4: Using the *Star-Gazers' Almanac*

The planisphere will enable students to determine what constellations are in the night sky on the date and time they plan to observe. Another useful tool, although more complicated, is the *Sky-Gazer 's Almanac* (SGA) (see Resource List.) The SGA is an astronomical graphic time table: a picture or graph of the times at which astronomical events occur. The Almanac shows the times for sunrise and sunset, and the rising, transiting, and setting times for the planets, several stars, and some other celestial objects. It also includes information about moonrise, moonset, and lunar phases. It is a more extensive aid in planning astronomical observations. Although the planisphere may ensure that the constellations you want to see are in the sky on the night you plan to observe, that will not be much help if the Moon is full that evening. With the SGA, you will be able to determine what planets are observable on any night of the year you RESOURCE choose, as well as the best nights for observing them.

More advanced students can read the explanation for using the SGA on the back of the graph itself. Note, however, that it contains two types of time corrections: one adjusts for daylight-savings time, and the other for how far East or West you are of the longitude marking your time zone. You will want to use the time corrections in Core Activity 3.3, as we have simplified them for you. Also, the activity is broken up into sections on the Sun, stars, Moon, planets, and meteor showers. You may prefer to introduce one section at a time or eliminate some altogether, depending on how much of the SGA you want your students to use.

The answers to some of the questions in the *Sky Gazer's Almanac* activity cannot be provided here, as they depend upon your particular geographical location for the time corrections. NOTE: The answers that are provided are accurate only for the 1998 Almanac. Some of the questions provided are not appropriate for other years; for instance, transit times of objects will change, different objects will transit, and planets do not appear in the sky at the same times or locations every year.

Starting in 1998, *Sky & Telescope* will be publishing a European *Sky Gazer's Almanac.* You could have some groups use both almanacs and compare the events in a single night, or over an entire year, for people living on opposite sides of the globe. Would your students expect many differences, or only a few? Can they predict what some of the differences might be?

Some possible answers

The Sun

1. Depends upon location.

2. Depends upon location.

3. The right side.

4. Eastern sky (actually somewhat north of east during winter, and south of east during summer.)

5. Depends upon location. Example: 6:00 AM with no time correction; ~5:44 AM in Boston.

6. Depends upon location. Example: 5:50 PM with no time correction; ~6:34 PM in Boston.

7. ~ Dec. 20th.

8. ~15 hours, including twilight. (~11½ hours, excluding twilight).

9. ~June 21st.

10. ~9 hours, including twilight. (~5 hours, 10 minutes, excluding twilight).

11. The length of night varies throughout the year due to the tilt of the Earth as it orbits the Sun.

The stars

1. It will lie along your meridian, the imaginary line drawn across the sky from North to South. Therefore it will also be as close to your zenith as possible, since your meridian marks the midpoint of your sky and the highest point to which objects can rise before beginning their descent.

2. ~December 14th–15th.

3. ~11:30 PM with no time corrections.

4. Stars are so far away that we cannot readily see their own motions through space. It is only their *apparent* movement we see, which is due to the rotation of the Earth in the course of an evening. In this apparent motion they all trace their own unique path straight up to the meridian and back down to the horizon without crossing each other.

The Moon

1. ~1:45 AM with no time corrections, third quarter in phase.

2. ~ September 4th–5th at 6:15 AM with no time corrections.

3. ~January 4th ~11:45 PM with no time corrections.

4. No. The Moon's location may not be in the same part of the sky as the Pleiades when it crosses the observer's meridian.

5. Various answers: i.e., January 11th at ~10:10 PM or November 23rd at 1:55 AM with no time corrections.

The Planets

1. December 13th–22nd when Mercury is at greatest elongation and brilliancy; also September and January in the morning, and the beginning of July in the evening.

2. ~February 20th or 21st.

3. December 7th.

4. September 7th is one possibility.

5. Distant planets appear stationary in the sky during any single night against the background pattern of stars. Their transit lines are straight.

6. The closer the planet, the more noticeable the movement. The movements and locations of Mercury and Venus relative to the Earth make it impossible for them to transit our meridian. Mars, outside the Earth's orbit, is close enough that its motions across the sky are not straight.

Meteor Showers

1. Depends on the season you use. For example, Leonids, Taurids and Orionids in the fall.

2. Depends upon above. For example, in the fall Orionids occur before the Sun comes up, and during a moonless night.

Chapter 4: Our Bearings in the Sky

Anasazi Recording of SN 1054 in Chaco Canyon , NM

Introduction

For centuries people have observed and recorded the changing patterns in the sky to keep track of the celestial events important to their survival or religious ceremonies. Prehistoric artifacts and remnants of astronomical observatories have been discovered around the globe, providing us with intriguing clues into how knowledge of sky motions developed into timekeeping and calendar systems, and how the sky and its motions became a source of rich and enduring mythologies. A fossilized mammoth tusk from a cave in France records the lunar cycle, inscribed 17,000 years ago during the last Ice Age. At Stonehenge, in England, the Sun rises over the heel stone during the summer solstice (the first day of summer). In Central America, the Mayans aligned their observatories according to their predictions of the first appearance of Venus in the predawn sky; their calculations were accurate for more than 100 years in advance. On White Mesa in northern Arizona, the Navajo appear to have recorded the Crab Nebula supernova explosion of 1054 AD with rock art drawings. At Fajada Butte, New Mexico, the Anasazi Indians arranged slabs of rock so that on the day of the summer solstice, a sliver of dagger-shaped sunlight shining through an opening in the rocks touched the center of a spiral chiseled into the rock. Keeping their eyes on the heavens to keep track of time and events on Earth, ancient skywatchers became the expert astronomers of their day.

Many ancient observers imagined the sky as a vast bowl or canopy, spinning once around the Earth each day. We know this picture is not correct, but it does help us to get our bearings. Think of the night sky as a great transparent spherical shell with all the stars glued to the inside of the sphere and the Earth sitting in the center. As the sphere appears to turn, the stars appear to move; however, they always maintain their positions on the transparent sphere relative to one another. For centuries, skywatchers have been familiar with the orbital motions involved with the Earth, Moon, and planets, and the apparent motions of the Sun and stars. Independently, they have devised and constructed complex calendars and time-keeping devices from their knowledge of the changing sky. Consistency between time and calendar systems of different cultures was not important, because astronomical knowledge was specific to the mythology and customs of each individual culture. Today most cultures are not isolated, they are organized into states and countries that share and exchange knowledge on a daily basis, and engage in scientific endeavors and studies together. A consistent world-wide system to accurately locate objects in the sky became a necessity, and the resulting celestial coordinate system, a roadmap of the sky, is used by professional and amateur astronomers to locate celestial objects.

Investigation 4.1a: Understanding the Motions of the Earth-Moon System

Your instructor will provide a light source. Standing near the light source, turn around so that you alternately face towards, then away from, the light. If you could draw a line from the bottom of your feet through the middle of your body to the top of your head, this would be your axis of rotation, the center around which you are turning. The Earth also rotates about its axis, taking 24 hours for each complete rotation. Stand still and have another student walk around you. The student is revolving around you. The Earth revolves around the Sun, taking 365.25 days, one year, for each complete revolution or orbit.

When you are facing the light source, the front of your body is illuminated—this is daylight on Earth. When you are facing away from the light, the front of your body is in shadow—this is like nighttime on Earth. Watch a friend rotate in front of the light. What do you notice about the pattern of shadow and light on your friend’s body? What does this pattern suggest about the pattern of day and night on the surface of the Earth?

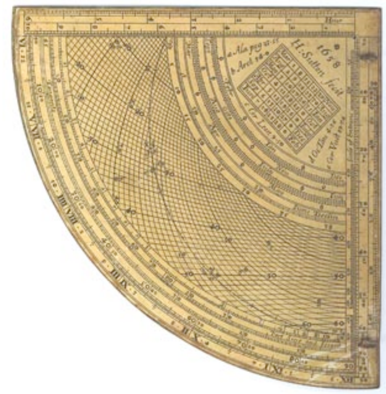
Use the objects at your disposal to answer the following questions. Does the Earth always cast a shadow? Does the Moon always cast a shadow? Do you notice phases on the Moon? Do other planets have phases? If so, which ones? Why or why not? As the Moon revolves around the Earth it also rotates, even though the same side is always facing the Earth. Can you demonstrate and explain this fact? The far side of the Moon is often referred to as the dark side of the Moon. Is it dark?

Using the members of your group and any other objects provided, recreate the sky motions of day and night, the Earth and Moon, stars and constellations. Be prepared to present your demonstration(s) to the other groups.

Investigation 4.1b: Understanding the Motions of the Stars and Constellations Across the Sky

You know that stars and constellations seem to move across the sky. How fast do they move? Locate a bright star that you can easily watch appear over the horizon, a building, or any easily identifiable reference point. Record the time that it just comes into view at your reference point. Do you think the star will appear at the same time every night? Repeat your observation and again record the time three days later. Does the star come into view at the same time? If not, what is the difference? Make five observations approximately three days apart, and take the average. What does this number represent? Remember that a point on the Earth's surface (except at the poles) travels 360° in one rotation, and the amount of time one rotation takes is commonly accepted as 24 hours.

Core Activity 4.2: Using a Quadrant to Measure Motion of the Moon, Stars, and Sun Across the Sky



The Sutton Quadrant, 17th

Over the centuries people have used sightings of the Sun, Moon, planets, and stars for a variety of purposes. One of the oldest devices for this purpose, the *quadrant*, dates back to about 240 BC. The quadrant is used to determine the altitude of a celestial object, in other words, its angular height (how many degrees it appears above the horizon). The quadrant enables the observer to locate celestial objects and determine information about celestial events, such as rising and setting times, motions, and position. Essentially, these simple tools were astronomical "clocks" used to devise calendars of celestial events. In the Islamic world simple quadrants served practical purposes in everyday life. They were used to determine times for prayer, ascending zodiacal constellations, positions of the Moon and Sun, and the alignments of these objects. Over time, improvements to the quadrant produced greater accuracy in observations. Celestial aids were developed in the 16th and 18th centuries to determine the time of night, schedule of tides, observer's latitude, and the time of the lunar meridian crossing.

Begin building your own quadrant by gluing the template on the next page to a piece of manila file folder. Cut out the quadrant. Cut a straw to the same length as the quadrant and attach with cellophane tape along the folded edge. Using a pencil, poke a small hole on the circle indicated on the quadrant. Pass some string through the hole and knot it. Then attach a washer or other small weight to the end of the string. Your quadrant is now ready to use.

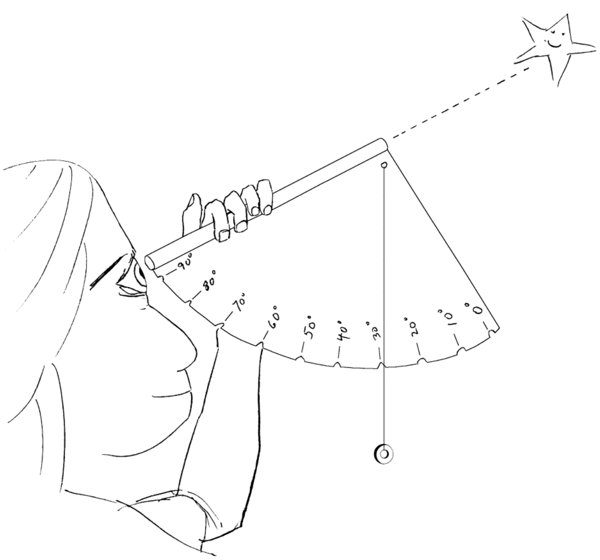
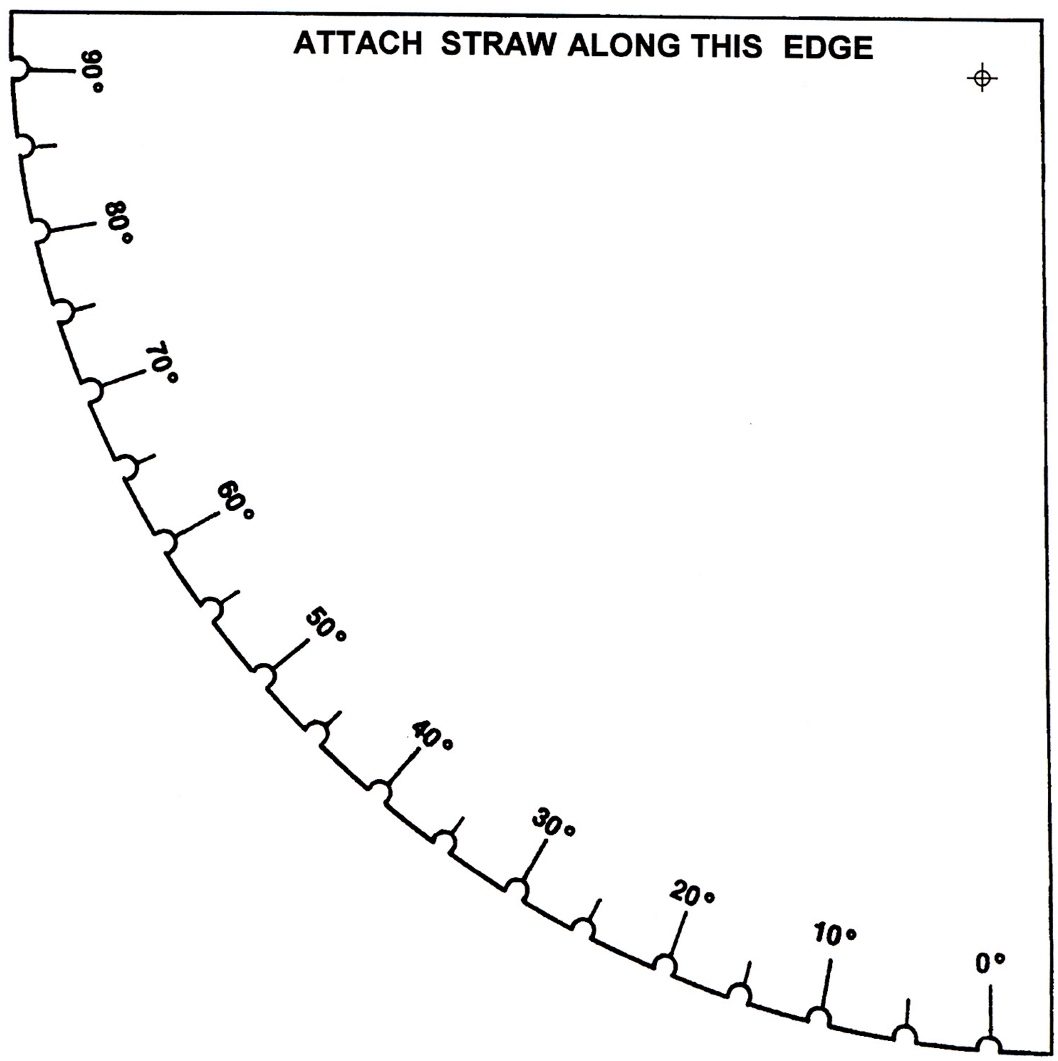


Figure 4.1, Mike Saladyga, artist

To use the quadrant to make vertical angular measurements (altitude): Hold the quadrant so that the straw is in your hand, with the end marked "90°" at your eye, and with the string hanging freely down. Sight the object you want to measure through the straw, then press the string against the quadrant card and note the angle at which the string lies on the card (Figure 4.1).

Practice using the quadrant. Determine the angular height (altitude) of a tall object such as a nearby building. Take three separate measurements and determine the average.

Quadrant Template



Besides measuring the altitude of celestial objects, the quadrant can also be used for measuring the angle separating any two celestial objects, such as stars. To make a horizontal angular measurement (azimuth), hold the quadrant horizontally and bring the end of the straw that is at the right angle of the quadrant to your eye. Through the straw, sight the first object you want to measure, and slide the string along the curved part of the quadrant so that it lines up with the second object. If the string is not in one of the notches, hold it carefully so as not to lose the measurement. (It is easier to have one person line up the quadrant and another hold the string.) Read what the angle is where the string lies: take this number and subtract it from 90°. The result is the angle separating the two objects in the sky. Determine the angular separation of any two objects in your vicinity for practice.

MEASURING THE MOTION OF THE MOON

Relative to the horizon, how much does the Moon change its altitude over a period of time? Choose a time to make a nightly or daily measurement of the Moon's altitude. Make three separate measurements at the same time each night or day and enter these data into a table, along with the direction of movement and the lunar phase (or shape). Calculate the average. The longer the observations are made, the more useful the data will be for answering questions and making predictions. What do you notice about the Moon's position from day to day? Does maximum height correspond with a particular phase? How much does the Moon move relative to a planet such as Venus or Jupiter? How much does it move relative to one of the pointer stars in the Big Dipper (in Ursa Major)?

MEASURING THE MOTION OF A CONSTELLATION, SUCH AS URSA MAJOR (THE ASTERISM IS THE BIG DIPPER)

Measure the altitude of two of the stars in the Big Dipper at 8:00 PM, 9:00 PM and 10:00 PM, taking three measurements and determining the average. Select the star at the end of the handle, and the pointer star at the other end. Do the same for Polaris and enter the data into a table. Take the measurements over an extended period of time (one week minimum). How much does the Big Dipper change from hour to hour? From day to day? From week to week? What is the motion of Polaris? Would you get the same amount of movement if you took your measurements from a different latitude?

MEASURING THE MOTION OF THE SUN

Figure 4.2, Mike Saladyga, artist

(**NOTE: NEVER** look at the Sun through the straw on the quadrant.The ultraviolet rays will damage the receptors in your eyes, causing blindness.) Hold the quadrant by the straw so that the angle markings face you, and the right angle end of the straw points in the direction of the Sun (see Figure 4.2 at right). Slowly move the straw: you will know you are close to getting a good reading as you see the shadow of the straw become shorter on your hand or on the paper. Continue moving the straw until a small circle of light forms on your hand or the paper; now the straw is pointing directly at the Sun. Now take a reading for the Sun's altitude. Take three measurements, record the data, and find the average. Take the measurements as close to noon as possible when the Sun is on the meridian and at its highest point in the sky for that day. Continue to take the data over a period of several weeks, or even for the entire school year. Does the noontime altitude change? Does the Sun ever get directly overhead? Where does the Sun get directly overhead? Does the altitude increase or decrease? Is this pattern of change related to the seasons? What pattern would develop in the Southern Hemisphere?

Core Activity 4.3: Why Constellations Appear in Different Places in the Sky at Different Times of the Year

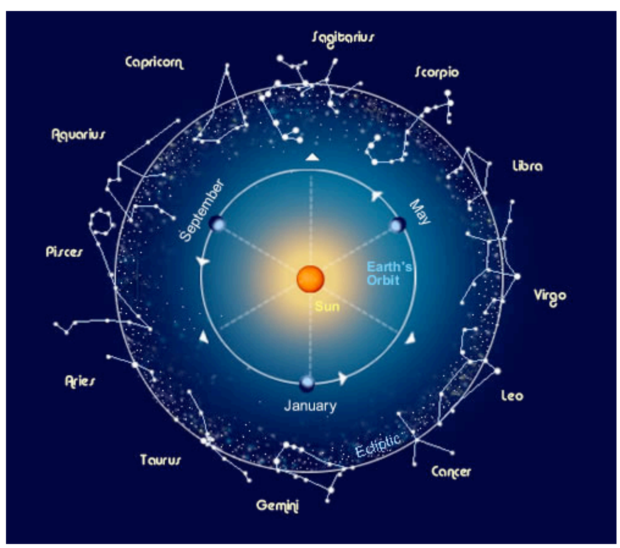
Introduction

Throughout the year we watch the orderly procession of constellations across the sky. We look for Orion to appear in the early winter, and know that Scorpio will inhabit the summer sky, spreading across it to dominate the southern horizon. March comes in like a lion—a lion named Leo, that is—that regally traverses the spring skies. In autumn there is Taurus the Bull, forever galloping into the sky to lead Orion into the winter skies once more. Why do these constellations seem to move across the sky in such a pattern? In this activity you will develop a model to demonstrate and explain this pattern.

Constructing the Model

Your class will first construct models of the zodiacal constellations, using drawings or any other art form of your choice if not given specific instructions. Each year as the Sun seems to travel on its imaginary path across the sky called the ecliptic, it completes one circuit through these zodiacal constellations.

After constructing your models, place them in a circle around the edges of the room with a large light source in the middle. Each quarter of the circle will then represent one of the seasons. Stand inside the circle between the constellations and the Sun. Since your horizon is a semicircle or 180 degrees, you cannot see the 180 degrees of constellations on the other side of the Sun, so have classmates stand in a straight line on either side of the Sun holding the sheets of paper or cloth provided to block your view of those. Turn counterclockwise, and during the nighttime when you are turned away from the Sun those are the constellations visible to you. The Earth also revolves counterclockwise around the Sun, so move in that direction to the next constellation. The barricade of students blocking your view of the constellations behind the Sun must rotate around one constellation in the same direction. As you turn to your night side you will see that one constellation has gone down in the west and another has risen in the east. As you revolve around the Sun during your "year," you will see the same procession of constellations that you see in the actual night sky during the year.



Seasonal Changes of Constellation Positions, Lunar & Planetary Institute

Abe Lincoln and the Almanac Trial

A three-week religious camp meeting conducted by a famous Methodist circuit rider named Peter Cartwright took place at Virgin's Cove, five miles northeast of the junction of Salt Creek and the Sangamon River, in Mason County, Illinois, during August of 1857. Around the fringes of the meeting, temporary bars were set up for the occasion, and drinking and gambling were on-going activities. At one of these outdoor saloons, a fight broke out at 11 p.m. on Saturday, August 29th. William Armstrong and James Norris had an altercation with James Preston Metzker, who mounted his horse and rode to the nearby home of a friend after the fight. He died there three days later of head injuries. Norris and Armstrong were arrested and indicted for murder. Norris was tried and convicted. Armstrong's mother traveled to the home of an old family friend in Springfield, Abraham Lincoln, and asked him to defend her son.

The murder trial of Armstrong took place at the Cass County courthouse in Beardstown, Illinois. The main prosecution witness stated that he was about 150 feet away from the fight but saw everything clearly by the light from a bright, nearly full Moon, high in the sky. Lincoln produced an almanac to prove that the Moon at 11 p.m. was going out of sight, within about an hour of setting, and not overhead as the witness claimed. After a short deliberation, the jury acquitted Armstrong. Exactly which almanac Lincoln consulted is not known. The two most often mentioned are *Jayne's Almanac* and *Goudy's Almanac*. Almost immediately serious allegations circulated that a fake almanac had been used, with the lunar phases and times of moonset altered to fit Lincoln's purpose. The story persisted because many townspeople at the time believed that Lincoln had prepared a fake almanac. Their almanacs showed a Moon nearly in mid-heavens at the hour of the fight, and the almanac Lincoln had consulted could not be found.

The Moon's position "nearly in mid-heavens" is a reference to the Moon's crossing of the meridian, called upper transit or upper culmination by astronomers. Almanacs often contained information on the times that the Moon was on the meridian. How could Lincoln prove the Moon was near the horizon and setting, since the people at the meeting had seen it with their own eyes, shining brightly, nearly full, and standing near the meridian?

The lunar phase and time of moonset on the night of August 29–30, 1857, has been calculated by many prominent astronomers. All found moonset times near 12:04 a.m. on August 30, 1857, supporting Lincoln's claim that the Moon at 11 p.m. on the 29th was low and near to setting. Two investigators, Donald Olson and Russell Doescher from the Department of Physics at Southwest Texas State University, repeated the calculations and discovered a coincidence involving a well-known 18.6-year lunar cycle and its effect on the lunar declination of August 29, 1857. In other words, the Moon on that night crossed the sky at its lowest elevation in 36 years. Their investigation explains the mystery of why so many people thought Lincoln had faked the almanac, and resolves the conflict between Lincoln's astronomical evidence and the recollections of the townspeople.

For an observer at a given latitude in the northern US, the length of time the Moon spends above the horizon depends primarily on its declination. The Moon "runs high" when it has an extreme northern declination, passing near the zenith, and staying in the sky a long time before finally setting in the northwest. The Moon "runs low" at the other extreme in declination, skimming low above the horizon, then quickly setting in the southwest. 1857 was a special year with respect to lunar declination. Every 18.6 years the most extreme lunar declinations occur, when the tilt of the Earth's axis and the tilt of the lunar orbit combine to produce lunar declinations exceeding 28° north and 28° south. On the night of the fight, the Moon was exceptionally low. As the Moon crossed the meridian on the evening of August 29th, its geocentric declination was –28.6°, and correcting for parallax for an observer in central Illinois gives an apparent lunar declination of –29.5°, almost the extreme value the Moon can attain. The Moon traveled from "mid-heavens" (the meridian) to the horizon in only a little more than four hours. Both Lincoln and the townspeople were right. Just before 8:00 p.m., the Moon crossed the meridian in the cloudless sky over Virgin's Cove. By the time of the fight, the Moon was dropping from view. "Honest Abe" did not use a false almanac.

Understanding cycles not only enables us to make predictions of events into the future. It also enables us to work backwards and know about events that happened in the past. There are several historical events that have important astronomical associations.

Henry Wadsworth Longfellow's poem, "The Midnight Ride of Paul Revere," mentions the Moon several times:

> he... Silently rowed to the Charlestown shore, just as the moon rose over the bay....
> The *Somerset,* British man-of-war; A phantom ship, with each mast and spar
> Across the moon like a prison bar...
> Where he paused to listen and look down A moment on the roofs of the town,
> And the moonlight flowing over all...
> A hurry of hoofs in a village street, A shape in the moonlight, a bulk in the dark....
> He saw the gilded weathercock Swim in the moonlight as he passed.

Are these statements about the Moon correct? After all, there are several inaccuracies in the poem. For instance, Revere is placed on the wrong side of the harbor, and he was involved in sending the lantern signal, not in receiving it. And Revere did not reach Concord, he stopped in Lexington. Is the poem also wrong about the Moon? Was the Moon rising as Revere crossed the river? Calculations show there was a bright waning gibbous Moon, 87% lit, in Boston on the night of April 18, 1775. The Moon was rising when Paul Revere crossed the harbor between 10 and 11 p.m. Computer simulations also show that the Moon had a southern declination of -18°, which, combined with Boston's latitude of 52° 22' north, caused the Moon to rise considerably south of east. When Revere crossed the harbor, roughly 45 minutes after moonrise, the Moon was low in the southeast. Anyone on the Somerset would have seen the Moon rising over the city of Boston, not over the open water of the bay, and would not have been able to see Revere row across the bay.

The Moon has also played a significant role in this century's wars. The timings of attacks and escapes were planned to coincide with appropriate lunar phases and tides. The German submarine U-47 was able to sneak into the Scapa Flow anchorage off Scotland and sink the battleship Royal Oak by gliding over rocks during an extraordinarily high tide caused by the coincidence of a new Moon with perigee. Amphibious assaults by the US Marines in the Pacific were timed for high tides to minimize the amount of exposed beaches the soldiers had to cross.

Tide conditions were crucial to the allied invasion of Normandy on the morning of June 6th, 1944: troops had to invade at extreme low tide so that the numerous beach obstacles could be avoided and cleared.

The Japanese attack of Pearl Harbor, Hawaii, was timed so a bright Moon would illuminate the carrier decks when the planes were launched; not a full Moon, however, which would have provided illumination all night long. The Japanese chose a Sunday morning with a waning gibbous Moon which rose in the evening, transited the local meridian after midnight, and remained bright and relatively high in the sky until dawn.

Core Activity 4.4: The Rotating Earth and the Sun's Apparent Motion Across the Sky

A. Shadow Stick Astronomy

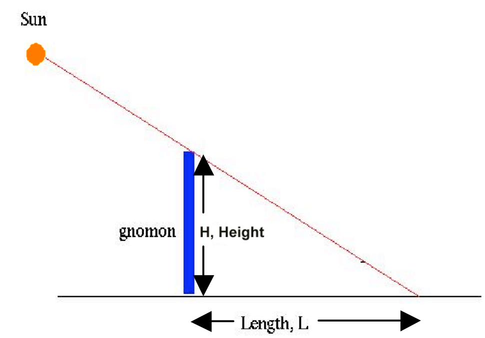


Fig.4.4

If you did not construct the quadrant from Activity 4.2, you may want to do so now. If you do not construct a quadrant, you can use the information in Table 4.1 to calculate the Sun's altitude instead by measuring the length of the stick and the length of the shadow. Construct a sundial by sticking a straight, sharpened wooden dowel or pencil onto the center of a stiff piece of poster board or manila folder with a small piece of clay. Make sure the stick is vertical. The vertical stick is called a gnomon (pronounced "nō'-mon"; the "g" is silent). Write the E-W and N-S directions on the paper. Take the sundial outside to a flat area that will have an unobstructed view of the Sun throughout the day. Use a magnetic compass to make sure that the compass directions are properly oriented. Clearly mark the place from which you are recording your information so that you can return to the same place for each measurement. Also remember to orient your paper in the same direction for each observation.

Every half hour or hour, beginning in the morning, mark on the paper the following information. The more data points you have, the easier it will be to answer the questions at the end of this activity.

1. The position of the end of the shadow made by the stick;

2. The time of day you are taking the measurement;

3. The altitude of the Sun measured with the quadrant, OR calculated by using a gnomon and Table 4.1 as follows:

    a. Measure the height of the gnomon (shadow stick).
    b. Measure the length of each shadow cast by the gnomon.
    c. Divide the length of each shadow by the height of the gnomon.
    d. Use the ratios you have just calculated to look up the corresponding angles on the table.

Table 4.1

ratio	angle°	ratio	angle°	ratio	angle°
0.00	0	0.58	60	1.73	30
0.02	89	0.60	59	1.80	29
0.03	88	0.62	58	1.88	28
0.05	87	0.65	57	1.96	27
0.07	86	0.67	56	2.05	26
0.09	85	0.70	55	2.14	25
0.11	84	0.73	54	2.24	24
0.12	83	0.75	53	2.36	23
0.14	82	0.78	52	2.48	22
0.16	81	0.81	51	2.61	21
0.18	80	0.84	50	2.75	20
0.19	79	0.87	49	2.90	19
0.21	78	0.90	48	3.08	18
0.23	77	0.93	47	3.27	17
0.25	76	0.97	46	3.49	16
0.27	75	1.00	45	3.73	15
0.29	74	1.04	44	4.01	14
0.31	73	1.07	43	4.33	13
0.32	72	1.11	42	4.70	12
0.34	71	1.15	41	5.14	11
0.36	70	1.19	40	5.67	10
0.38	69	1.23	39	6.31	9
0.40	68	1.28	38	7.12	8
0.42	67	1.33	37	8.14	7
0.45	66	1.38	36	9.51	6
0.47	65	1.43	35	11.43	5
0.49	64	1.48	34	14.30	4
0.51	63	1.54	33	19.08	3
0.53	62	1.60	32	28.64	2
0.55	61	1.66	31	57.29	1

After all the data have been collected, draw a smooth line connecting the points at the end of the shadows and measure each distance from the base of the shadow stick to the end of the shadow. Then answer the questions on the next page and discuss your results with the other groups.

1. Is the line connecting the points straight or curved?

2. Does the line curve away from the stick or around the stick?

3. Graph the altitude of the Sun versus the time the measurements were taken. At about what time was the Sun at its highest altitude?

4. At about what time was the shadow cast by the Sun the shortest?

5. Is there a relationship between the length of the shadow and the altitude of the Sun?

6. How would your results differ if you were recording your observations six months from now?

7. When and where would you have to be to have no shadow cast at some point along your graph?

8. Can you determine compass directions based on your observations?

9. Is your shadow always behind you?

10. How can shadows be used to tell time?

11. What problems would we encounter if we used a sundial to tell time?

12. When and why were sundials developed? Are there different kinds of sundials?

B. Shadows on a Sphere

You will be given a clear plastic hemisphere. Imagine that you are standing inside, at the center; the dome represents the sky. You are now going to track the Sun's path as it actually appears to you in the sky.

Glue a plain piece of paper onto a stiff piece of cardboard and place a small "x" in the center of the paper. Attach your hemisphere over the base with tape and mark the cardinal directions N, S, E and W on the paper and also on the base of the hemisphere. Make sure the hemisphere is centered over the base, with the top of the sphere directly over the "x" and firmly attached.

Place the hemisphere on a flat surface that will be in direct sunlight for as long as you intend to take measurements. With a compass, orient the hemisphere so that the North side of the hemisphere is actually pointing North. You may want to draw an outline around the cardboard with chalk if possible in case the hemisphere is moved. If this is not possible, check frequently to make sure that the hemisphere North is pointing North. Start this activity in the morning and take data as long as possible throughout the day.

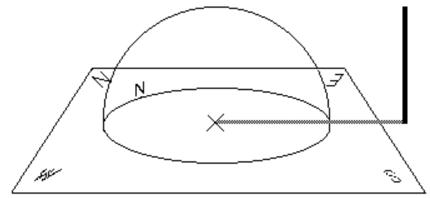


Fig. 4.5

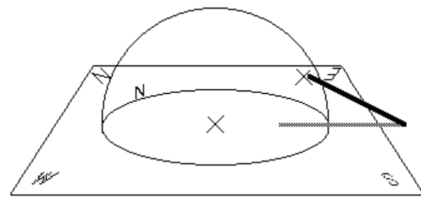


Fig. 4.6

Holding it vertically with the sharp end up, move a sharp pencil around on or near the cardboard until the shadow cast by its tip falls exactly on the center of the base diagram (see Figure 4.5). Without moving the base of the pencil, lean it over until the tip of the pencil touches the hemisphere. Make a dot with a non-permanent marker where the pencil touches the hemisphere at the same time that the shadow of its tip falls exactly on the center of the base diagram (see Figure 4.6). Place a number 1 on the dot on the sphere and in a notebook enter the time that the first data point was plotted. Continue to plot points and record the time every half hour.

When you are finished with the series of plots, trace them on the *inside* of the globe for a permanent record. Then erase the marks on the outside when it is time to take another series of observations next month, or next season. On the inside of the globe connect the plotted points with a solid line and label the line with the date. Answer the following questions:

1. From what direction did the Sun rise and in what direction did it set?

2. Where was the Sun's position at noon (what was the approximate angular height)?

3. Compare and contrast the shape of the path of the Sun across the dome with the shape of the path of the Sun in the shadow stick activity. Are the results the same? Explain what you see.

4. You may want to repeat this activity every month using different colors each time you draw the line on the inside of the globe, or repeat it once each season.

   Predict what the changes would be and see how closely your results agree.

5. Would your results change with longitude? Latitude? How far away would you have to be and in what direction to detect a difference?

Mapping the Sky: The Celestial Sphere Coordinate System

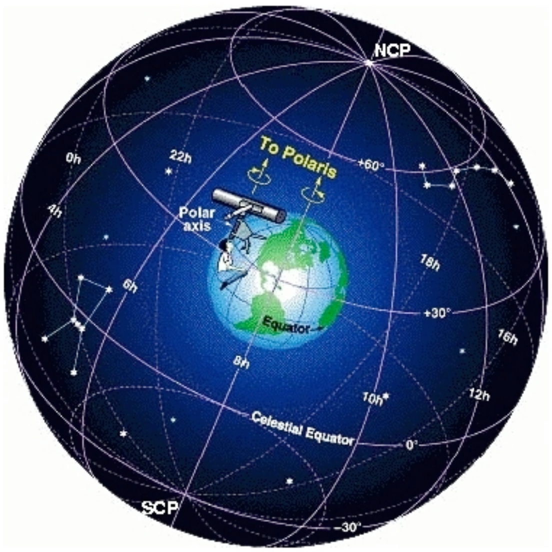


Figure 4.7

The *celestial sphere* is an imaginary, hollow, transparent sphere centered on the Earth (see Figure 4.7). The Earth's terrestrial coordinates are extended out onto the celestial sphere and superimposed upon its surface. The Earth's equator becomes the celestial equator (CE), the north terrestrial pole becomes the north celestial pole (NCP), and the south terrestrial pole becomes the south celestial pole (SCP). The terrestrial coordinates of longitude and latitude are also extended to the celestial sphere and are called *right ascension (RA)* and *declination (Dec)*, respectively (refer to Figure 4.8 below). Now all celestial objects can be located on the celestial sphere, an imaginary map with the specific coordinates of right ascension and declination. We can now use these coordinates to locate all objects in the sky exactly the same way we locate places on Earth—by using longitude and latitude.

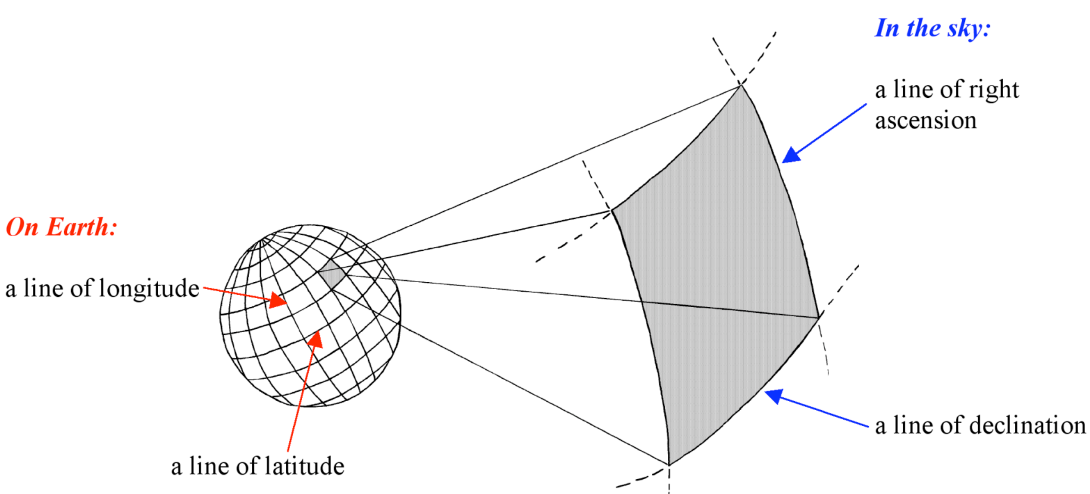


Figure 4.8

The celestial sphere is a geocentric model—it represents sky motions as they appear from Earth, and not as they actually are. Remember that even though models are useful, they also include distortions: the Earth is rotating, not the sky. The apparent path of the Sun, the ecliptic, is also superimposed onto the surface of the sphere, and so both the Sun and the sky appear to move around the Earth; the celestial sphere is a reflection of the Earth's rotation and tilt. The ecliptic is inclined from the celestial equator by 23½°, and has four important points along its path. The point 23½° below the celestial equator (Northern Hemisphere) is the winter solstice, and the point 23½° above the celestial equator (Southern Hemisphere) is the summer solstice. The two points where the ecliptic intersects the celestial equator are the vernal (spring) equinox and the autumnal (fall) equinox (see Figure 4.9 below). At the vernal equinox, the Sun starts its ascent into the Northern Hemisphere, climbing to 23½° above the celestial equator by the summer solstice, when the duration of daylight is the longest. The Sun then descends past the autumnal equinox into the Southern Hemisphere as far as 23½° below the celestial equator to the winter solstice, when the duration of daylight is the shortest in the Northern Hemisphere, before starting the climb back to the vernal equinox. The equinoxes have equal hours of day and night.

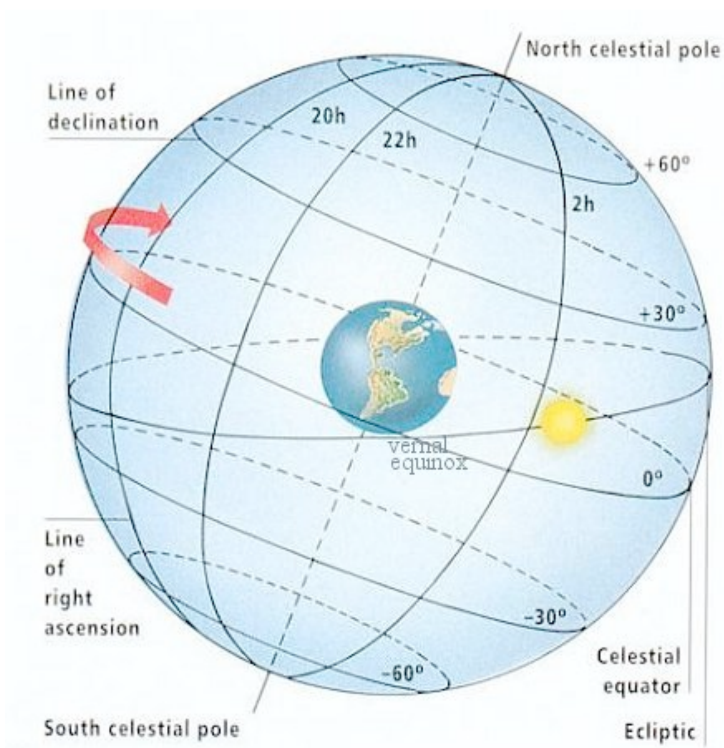


Figure 4.9

Declination is measured, like its terrestrial equivalent of latitude, as the angle north or south of the celestial equator in degrees, minutes, and seconds of arc. Declination goes from 0° at the celestial equator up to +90° at the North Celestial Pole and down to –90° at the South Celestial Pole. Right ascension, corresponding to longitude on Earth, is not measured in degrees as it is on Earth, nor is it measured east or west. It is measured in units of time: hours, minutes, and seconds eastward. Right ascension goes from 0 hours, located at the vernal equinox, in one-hour increments to 23 hours; 24 hours is the same as 0 hours, which brings us back to the starting point at the vernal equinox. The vernal equinox, 0^h RA, corresponds to the prime meridian on Earth, the line of longitude that runs through Greenwich, England (refer to Figure 4.10 on the next page). The 0^h right ascension line on the celestial sphere is also called the celestial meridian and runs through the constellation of Pisces, the fish, in the Northern Hemisphere.

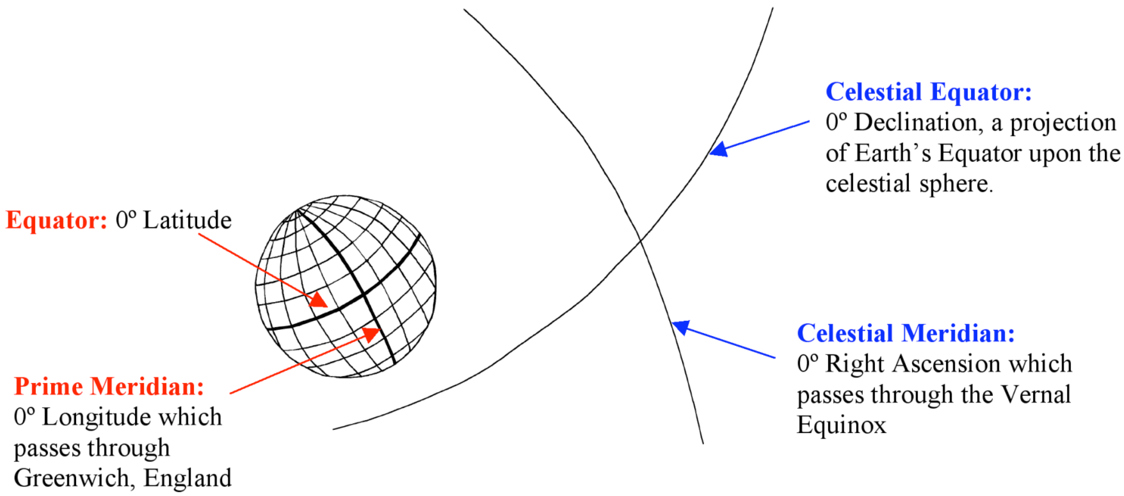


Figure 4.10

Since there are 360° in a circle and 24 hours of right ascension, 15° corresponds to one hour of time. The Earth rotates 15° every hour, and after a 24-hour period has rotated through all 360°, i.e. 24 hours of right ascension. This is the timekeeping device referred to as *sidereal [“sī-dir′-ē-al”] time*, or telling time by the stars. The *sidereal day* officially starts at midnight, when the vernal equinox (0^h RA), passes over your meridian, and ends the following midnight upon returning to your meridian. Therefore, one sidereal day is equal to one rotational period of Earth. Twenty three hundred (2300) hours (11:00 PM) means that 23 hours right ascension is at your meridian, and at fifteen hundred (1500) hours (3:00 PM), 15 hours right ascension is at your meridian. (A sidereal day begins at midnight, so 24^h RA = 12:00 AM, 1^h RA = 1:00 AM, 12^h RA = noon, 15^h RA = 3:00 PM, 18^h RA = 6:00 pm and 21^h RA = 9:00 PM.)

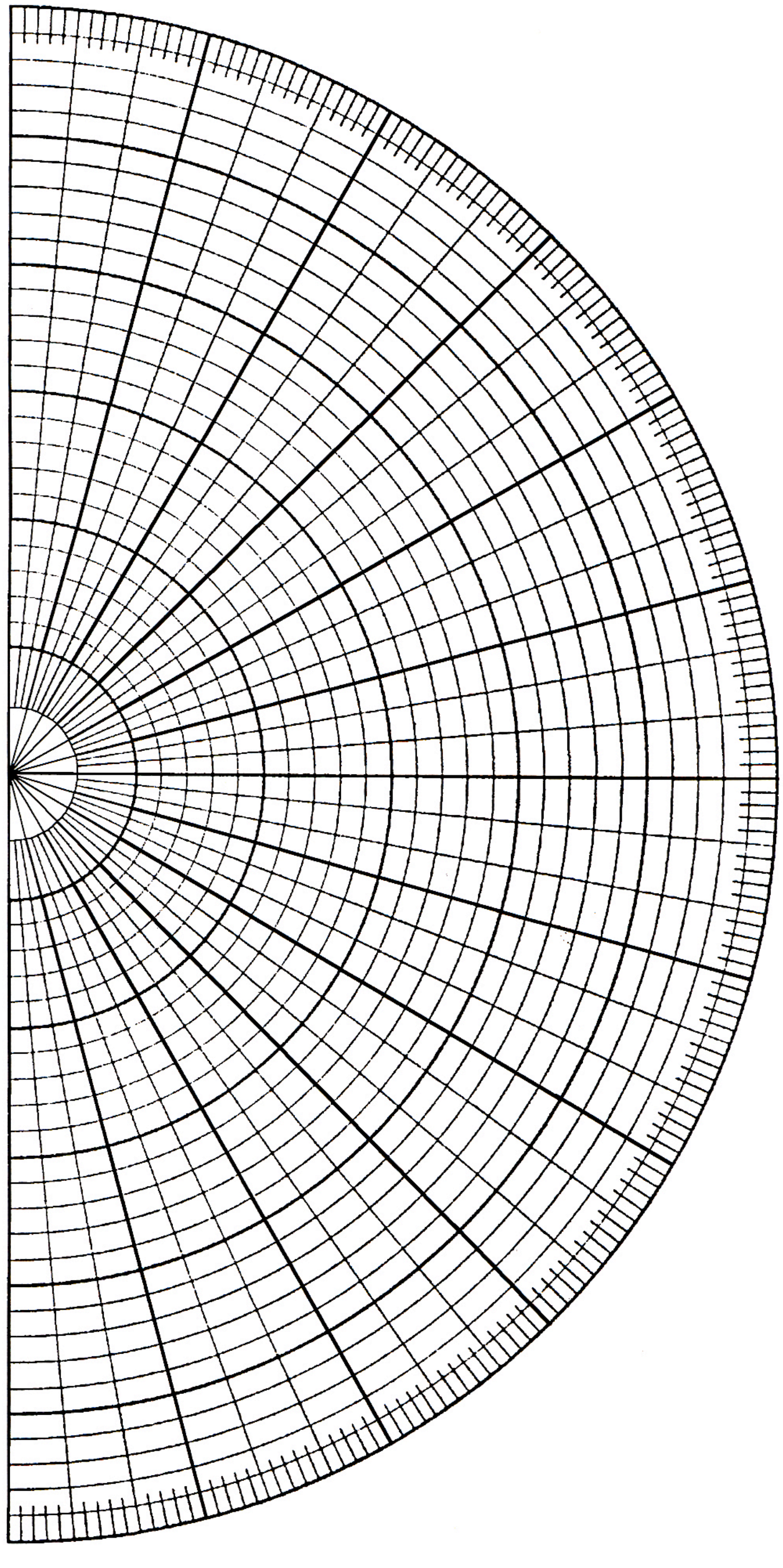
Core Activity 4.5: Constellation Plots

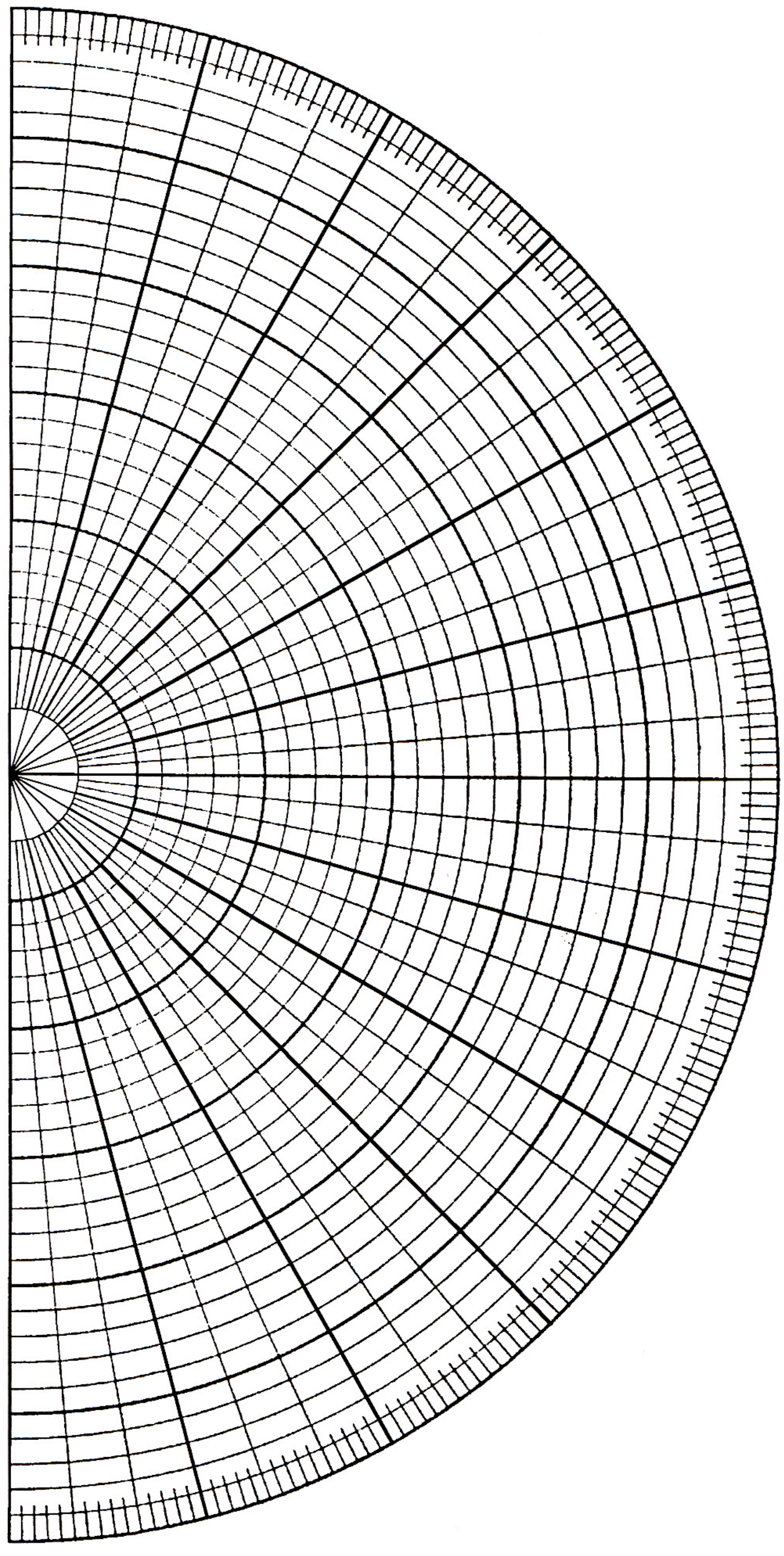
The purpose of this activity is to construct a constellation map with the polar coordinate graph paper provided. The center of the paper is the north celestial pole, the circles are the lines of declination (Dec), and the radial lines are the lines of right ascension (RA). Read the next three paragraphs before you begin.

1. Assemble the polar coordinate graph paper provided by your instructor and label the coordinate system on the polar coordinate graph paper, along with the appropriate units of measurement; then plot the stars listed in the constellation coordinates charts using an appropriate size scale to indicate their apparent magnitudes.

2. Connect the lines for the stars within each constellation to form the familiar asterism and/or outline. It is less confusing to plot the stars and connect them one constellation at a time. You may decide not to connect all stars within a constellation. Some variable stars have been included for some of the constellations, and you may not recognize these as part of the familiar patterns you use to find constellations, although sometimes variables are part of the asterism (such as Polaris). Astronomers use an open circle to plot variable stars. You should do the same, and perhaps color the circle with red ink to make it stand out. As this coordinate system may be unfamiliar and confusing at first, you should use pencil to locate the stars and use ink only after you have ascertained that the constellation outlines are correct by referring to a star chart.

3. The first four constellations are circumpolar for the Northern Hemisphere (Ursa Major, Ursa Minor, Cassiopeia, Cepheus); the fifth constellation, Cygnus, is part of the asterism for the Summer Triangle, and the sixth constellation, Auriga, is a winter constellation.





CONSTELLATION COORDINATES

CONSTELLATION	STAR NAME			MAGNITUDE	RA	DEC
Ursa Minor	**α	alpha	Polaris	2.02	$01^h\ 22'$	$+88°\ 46'$
	β	beta	Kocab	2.08	$14^h\ 51'$	$+74°\ 33'$
	γ	gamma	Pherkad	3.05	$15^h\ 21'$	$+72°\ 11'$
	δ	delta		4.36	$18^h\ 04'$	$+86°\ 37'$
	ε	epsilon		4.23	$16^h\ 56'$	$+82°\ 12'$
	ζ	zeta		4.32	$15^h\ 48'$	$+78°\ 06'$
	η	eta		4.95	$16^h\ 20'$	$+75°\ 59'$
Ursa Major	α	alpha	Dubhe	1.79	$10^h\ 58'$	$+62°\ 17'$
	β	beta	Merak	2.37	$10^h\ 56'$	$+56°\ 55'$
	γ	gamma	Phad	2.44	$11^h\ 48'$	$+54°\ 15'$
	δ	delta	Megrez	3.31	$12^h\ 10'$	$+57°\ 35'$
	ε	epsilon	Alioth	1.77	$12^h\ 50'$	$+56°\ 30'$
	ζ	zeta	Mizar	2.27	$13^h\ 20'$	$+55°\ 26'$
	η	eta	Alkaid	1.86	$13^h\ 44'$	$+49°\ 49'$
	**R	UMa		10.25	$10^h\ 37'$	$+69°\ 17'$
	**S	UMa		9.75	$12^h\ 38'$	$+61°\ 38'$
	**Z	UMa		7.80	$11^h\ 50'$	$+58°\ 25'$
Cassiopeia	α	alpha	Shedir	2.23	$00^h\ 35'$	$+55°\ 59'$
	β	beta	Caph	2.27	$00^h\ 03'$	$+58°\ 36'$
	**γ	gamma		2.47	$00^h\ 51'$	$+60°\ 11'$
	δ	delta	Ruchbah	2.68	$01^h\ 19'$	$+59°\ 43'$

** Variable Star (average magnitudes)

CONSTELLATION	STAR NAME		MAGNITUDE	RA	DEC
Cassiopeia	ε Epsilon		3.38	01^h 47′	+63° 41′
(cont.)	**R Cas		9.80	23^h 53′	+50° 49′
	**V Cas		10.05	23^h 06′	+59° 09′
Cepheus	α alpha	Alderamin	2.44	21^h 16′	+62° 10′
	β beta	Alfirk	3.23	21^h 27′	+70° 07′
	γ gamma	Alrai	3.21	23^h 35′	+77° 04′
	**δ delta		3.75	22^h 25′	+57° 54′
	ε epsilon		4.19	22^h 11′	+56° 33′
	ζ zeta		3.35	22^h 07′	+57° 43′
	ι iota		3.52	22^h 46′	+65° 40′
	**T Cep		8.15	21^h 08′	+68° 05′
	**S Cep		9.75	21^h 53′	+78° 09′
Cygnus	α alpha	Deneb	1.25	20^h 38′	+44° 55′
	β beta	Albireo	3.08	19^h 26′	+27° 44′
	γ gamma	Sadr	2.20	20^h 18′	+39° 56′
	δ delta		2.87	19^h 41′	+44° 53′
	ε epsilon	Gienah	2.46	20^h 42′	+33° 35′
	ζ zeta		3.20	21^h 08′	+29° 49′
	η Eta		3.89	19^h 52′	+34° 49′
	θ theta		4.48	19^h 33′	+49° 59′
	ι iota		3.79	19^h 27′	+51° 31′
	κ kappa		3.77	19^h 14′	+53° 11′
	**X Cyg		6.47	20^h 39′	+35° 13′
	**χ Cyg (chi Cyg)		9.30	19^h 46′	+32° 39′
	**W Cyg		7.85	21^h 32′	+44° 55′

CONSTELLATION	STAR NAME		MAGNITUDE	RA	DEC
Auriga	α alpha	Capella	0.08	05^h 09′	+45° 53′
	β beta	Menkalinan	1.90	05^h 52′	+44° 56′
	γ gamma		1.65	05^h 20′	+28° 31′
	θ theta		2.62	05^h 52′	+37° 12′
	ι iota	Hassaleh	2.69	04^h 50′	+33° 28′
	**R Aur		10.50	05^h 09′	+53° 28′

**Variable Star (average magnitudes)

Coordinates and magnitudes (epoch 1900) obtained from the *Bright Star Catalogue*, 4th revised edition. Dorrit Hoffleit, Yale University Observatory, 1982.

Activity 4.6: Plotting the Actual Positions of the Planets

You can construct a model with a different perspective of the Solar System by using the current celestial coordinates from information provided by your instructor or from a resource such as the latest *Sky & Telescope* magazine, which each month has a table that lists the positions (right ascension and declination) of the Sun and planets. Select a date that is closest to today. Your model will then accurately portray the present positions of the planets relative to Earth. As with all Solar System models, this one also has distortions. Since you will be constructing the positions of the planets from the perspective we have here on Earth, the Earth—not the Sun—will be the center of the model.

If this is a paper model:

On the same polar coordinate paper that you used for the Core Activity 4.5 Constellation Plot, label the coordinates of RA and declination in the same manner as you did in the circumpolar coordinate activity. The Earth will be at the center with the lines of RA radiating outward. Label the RA lines from 0 to 23 hours. Using a scale of 1 cm = 1 AU, indicate on the grid the positions of the Sun and planets with different colored pencils.

If this is an outdoor model:

Lay out your grid with the materials provided, marking the hours of RA as above. The scale is now 1 m = 1 AU. Calculate the appropriate distances for the Sun and planets and place markers at their positions. If you have a way of elevating the markers, you can construct a 3-D model of the Sun and planets by taking the declination coordinates into account. Don't forget that numbers for declination can also be negative. You may also want to add the zodiacal constellations around the outside in the appropriate locations. Stand in the middle (Earth), rotate counterclockwise, and watch the hours of RA seem to rotate clockwise through the sky.

Answer the following questions:

1. What planets should you be able to see tonight? Why?
2. In what constellation is the Sun?
3. What do you think will be the RA of the Sun in 3 months?
4. What constellations will be visible in the night sky in 3 months? In 6 months?

Astrology or Astronomy?

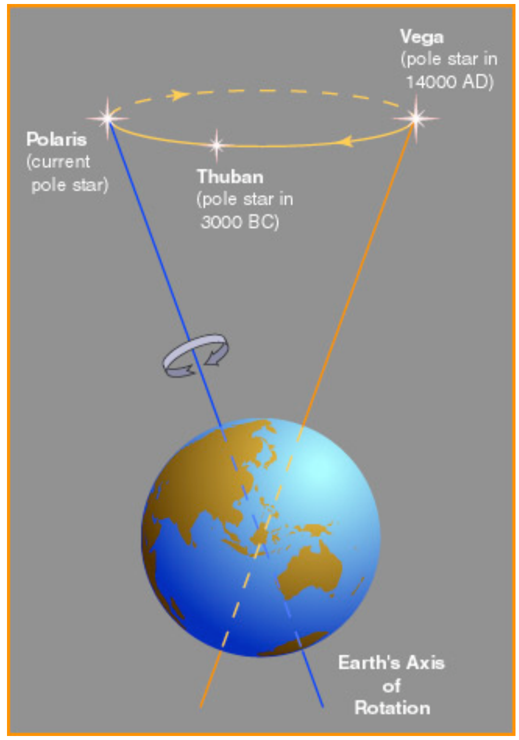
The most obvious and widespread invention of astrology is the horoscope. It is built upon the premise that the constellation behind the Sun at the moment of birth determines the personality, characteristics, and lifelong events of a child. The zodiacal constellations are those that lie along the ecliptic, the apparent path of the Sun, and therefore disappear behind the Sun for approximately one month each year. The Earth moves about 30° per month in its yearly orbit around the Sun.

Astrologers attach great influence to these zodiacal constellations, called "Sun signs," and use them to produce horoscopes that appear in a large variety of books and magazines which are prominently displayed in drugstores, grocery stores, and bookstores. A large percentage of newspapers in the United States publish either daily or monthly columns on astrology. The code of standard astrology states that "A precise astrological opinion can not honestly be rendered with reference to the life of an individual unless it is based upon a horoscope for the year, month, day and time of day plus correct geographical location of the place of birth of the individual." This statement alone renders all daily forecasts in newspapers null and void. However, even with all information pertinent to the moment of birth, the prophecies of astrology are still fraudulent.

Predictions made by astrologers are so general and vague that most people can usually make associations with their daily activities. But what about the specific predictions made by the most popular astrologers? How correct are they? Astronomers from Colorado State University examined 3,011 specific predictions by famous astrologers and determined that only 10 percent of them actually occurred. Of all such scientific studies to date, every single one has proven that astrological claims have no validity. If the stars lead us to incorrect predictions 90 percent of the time, they hardly seem to be the right guides to help us through life's uncertainties. Stars are not magical, nor are they gods. Stars are other suns similar to our Sun, remote balls of gas undergoing nuclear fusion, as unconcerned with human affairs as nuclear reactors are here on Earth. Unlike our remote ancestors, we understand the fundamental forces of nature and know how they affect galaxies, stars, planets, and people.

The difference between astrology and astronomy is often not well understood, and astrologers have made skillful use of this confusion. The astrological community utilizes scientific terminology and quotes people from seemingly reputable scientific organizations to reinforce the idea of the legitimacy of their beliefs. It is unfortunate that in the minds of many people astrology is confused with true science. The result of this confusion is to prevent people from developing truly scientific habits of thought that would help them understand the natural, social, and psychological factors that are actually influencing their destinies. Horoscopes are flights from reality, a substitute for honest and sustained thinking. Our destinies are shaped by our own actions in this world; our fate rests not in the stars, but in ourselves.

If you pay attention to your horoscope in the daily newspaper, you are in for a surprise. Since astrologers developed the idea of "signs of the zodiac" more than 2000 years ago, the Earth's position in space with respect to the stars has changed.



The Earth undergoes a complicated motion involved with its rotation called precession. It is similar to a spinning top that starts to wobble when it slows down. As the Earth rotates about its spin axis, it also wobbles, tracing the pattern of a cone in the sky. One wobble takes ~26,000 years to complete.

During this 26,000 year circular sweep of the Earth's North Pole, the pole star keeps changing. In ~13,000 years, the star most directly above the North Pole will be Vega, in the constellation Lyra, the Harp. At that time, the summer triangle will be circumpolar for the northern hemisphere. The Big and Little Dippers will rise and fall with the seasons, and Orion and the other winter constellations will become summer constellations.

Because of precession, the apparent positions of the zodiacal constellations used as Sun signs by astrologers have shifted by more than 25° during the past 2000 years. Each sign or constellation no longer represents the time when the Sun is in the related constellation. So you will discover that, for example, on October 25th the Sun is actually in Libra, not Scorpio as your horoscope tells you. Even the constellations that form the zodiac sometimes change. There are actually 13 zodiacal constellations, not 12! However, since there are 12 months in a year, astrologers want only 12 Sun signs and simply disregard number 13. People born at the end of November or beginning of December are actually associated with Ophiuchus, the serpent holder.

Current approximate dates of the constellations of the zodiac:

January 22 - February 22	Capricornus
February 22 - March 22	Aquarius
March 22 - April 22	Pisces
April 22 - May 22	Aries
May 22 - June 22	Taurus
June 22 - July 22	Gemini
July 22 - August 22	Cancer
August 22 - September 22	Leo
September 22 - October 22	Virgo
October 22 - November 25	Libra
November 25 - December 5	Ophiuchus
December 5 - December 22	Scorpius
December 22 - January 22	Sagittarius

SPACE TALK

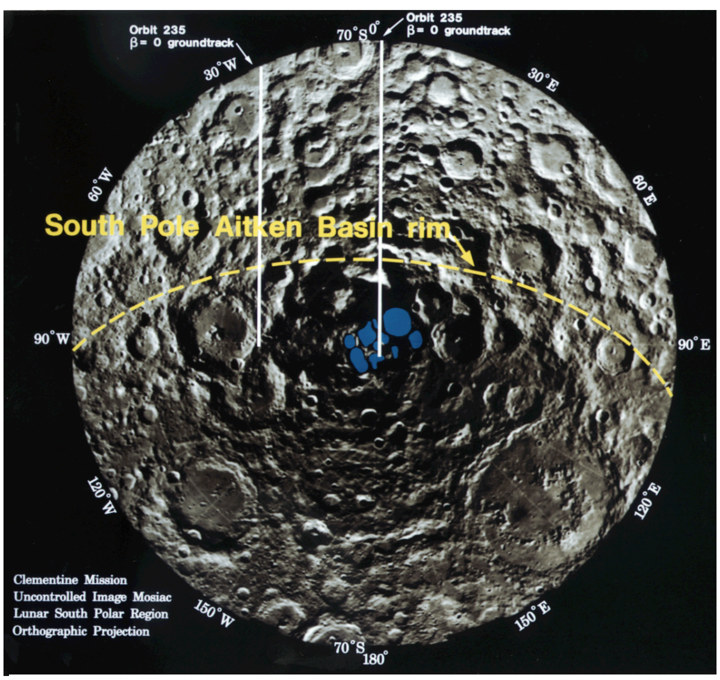
Humankind has always found the Moon fascinating. Ancient peoples thought of the Moon as a goddess, a clock, a calendar. Various enduring mythologies have imbued the Moon with the power to create fertility, love, and insanity. Writers have found the Moon a rich subject for fiction. Kepler took us to the Moon for the first time in his story "The Dream." Later, Jules Verne and dozens of other science fiction writers followed with their own fanciful versions of trips to the Moon.

Today we are no less fascinated with the Moon than were our historical counterparts. On June 20th, 1969, the world watched with wonder and amazement as Neil Armstrong and Buzz Aldrin stepped down from the Apollo 11 lander and left the first footprints on the surface of the Moon in Mare Tranquillitatis (Sea of Tranquility). Would we soon colonize the lunar surface the same way that nations in the past had colonized remote foreign lands? We have landed, walked and driven over the lunar surface, and brought back Moon rocks and soil samples. Equipment left behind by Apollo missions still monitors the Moon for moonquakes and reflects laser beams from Earth back to Earth to measure continental plate movement.

With no atmosphere, bombarded with radiation, and temperatures ranging from 230°F by day to -300°F at night, the Moon is not an inviting environment. And yet we still watch the Moon with interest, observing its lunar phases wax and wane. We see the Moon being eclipsed by the Earth's shadow, and the disc of the Sun covered by the disc of the Moon. These motions were once watched with fear and terror and were considered to be omens of disaster. Now we watch them with pleasure and a reassuring sense of familiarity.

Lunar motions are much more complicated than can be easily detected. It is well-known that the same side of the Moon always faces Earth. Most satellites are locked into the same relationship with the planets they orbit. The tidal forces exerted by the planets alter the **rotation** rates of their satellites until the rotation rate is equal to the rate of **revolution** (orbital period). This phenomena is called **synchronous rotation**. However, we can actually see more than 50% of the Moon's surface due to another set of motions called librations. The combined effects of the librations, or rocking motions, allow us to see 59% of the lunar surface. The Moon displays real physical librations due to the interaction of the tidal forces of Earth and the uneven mass distribution on the Moon. Tidal forces produced by the Sun's gravitational field cause the Earth to wobble (**precession**); tidal forces due to the Earth's gravitational field cause the Moon to rock (librate). The other types of rocking motions the Moon exhibits are not real, only apparent—the result of the Moon being observed from slightly different directions during different times of the year. The Moon's axis of rotation is tilted ~7° from its orbital plane around the Earth. As a result, every month the lunar features seem to shift from north to south as we are able to see from ~7° over the northern polar region to ~7° under the southern polar region. This apparent up-and-down rocking motion is called *libration in latitude*. The Moon also displays a side-to-side rocking motion called *libration in* *longitude*. This occurs because the Moon is in an elliptical orbit around the Earth. The Moon's rotation rate remains constant; however, its orbital rate does not. When the Moon is at its closest approach to the Earth, called **perigee**, its orbital speed is at maximum; when the Moon is at its farthest approach to Earth, called **apogee**, its orbital speed is at minimum. Since the rotational speed of the Moon does not change but its orbital speed does, sometimes its orbital position runs ahead of its rotational position, and sometimes behind. This allows us to see ~8° around the west **limb**, or edge or the Moon, and then ~8° around the east limb.

You can observe and record the apparent changes caused by librations in lunar features such as craters and **maria**, or seas. The dark patches on the Moon, called maria (Latin for seas), were once thought to be oceans. They are actually areas of basaltic materials, outflows from extinct volcanic activity. Both the maria and the lighter areas, called **highlands**, are heavily cratered by meteorites. If you spend some time looking at the Moon you will notice that during full Moon when the face is bright, the surface features seem flat. If you look at these same features when they appear near the **terminator**—the line that divides the lit and unlit parts of the Moon—during any other phase, they will become more distinct, and you can then see that craters have raised rims and deeper centers than the surrounding topography. The line of shadow that marks the terminator brings topographical features into raised relief because the Sun is shining on the Moon at an angle. It is harder to see lunar features near the limb at night if a large amount of surface is reflecting sunlight. You may find it easier during twilight. Select an object near the limb such as Mare Crisium or the crater Aristarchus to study and to draw. Draw the same object at different times throughout the month and you will have an observational record of lunar librations.



Clementine Mission Image with Lunar Ice Indicated in Blue

The southern polar region of the Moon could still be labeled "Luna Incognita"—unfamiliar territory. Lunar missions have either been in near-equatorial orbits or occurred while the region was in darkness. The southern polar region is now being studied as a possible site of lunar ice. The Sun never deviates more than ~2° from the equator of the Moon, and as a result, there are polar regions that have never been touched by sunlight. In 1994 the lunar spacecraft Clementine transmitted data indicating that ice might exist in this area, invoking once again visions of the colonization of the Moon.

Chapter 4: Our Bearings in the Sky

Summary

The first part of this chapter describes and explains the daily and yearly motions of the Sun, Moon, and stars, and introduces some simple activities to illustrate them. Students construct and use some additional simple astronomical tools, including the quadrant and gnomon. Since many students have significant misconceptions about the sky motions, hopefully this section of the chapter will be included in some part of your science curriculum. The video "Private Universe" shows how prevalent these misconceptions are even among highly educated adults and is a good introduction to the chapter. (See Resource List for details.) The second part of the chapter addresses the celestial sphere and its coordinate system for accurate locations of celestial objects, and is intended for older students. It is optional and not an essential core element for the remainder of the curriculum.

RESOURCE

Terminology

apogee	libration	quadrant	sidereal time
celestial sphere	limb	revolution	synchronous rotation
declination	maria	right ascension	terminator
gnomon	perigee	rotation	
highlands	precession	sidereal day	

Common Misconceptions

1. *All stars in each constellation are the same distance from the Earth.*
2. *Constellations change due to Earth's rotation.*
3. *The Sun is directly overhead at noon.*
4. *We always see only the same face of the Moon.*
5. *The Moon does not rotate.*
6. *The far side of the Moon is always dark.*

SUGGESTIONS FOR THE POSTER PAGES, INVESTIGATIONS, AND ACTIVITIES

Investigation 4.1a: Understanding the Motions of the Earth-Moon System

The purpose of this investigation is to give students an understanding of the basic motions of rotation and revolution, and to address possible misconceptions about the

Moon. The room needs to be darkened as much as possible, and a bright light source placed in the middle of the room. Have materials such as polystyrene balls available. These work better than Styrofoam, as the contrast between light and dark is much more distinct. Oranges also work well and have a more realistic surface topography. A large orange for the Earth and a ping-pong ball for the Moon will provide a reasonable scale. A small dowel can be glued to the ping-pong ball. Other than pencils to stick into the orange or styrofoam balls, the only additional element you will require is the participation of students themselves. Have them recreate the motions of the Earth-Moon system and show lunar phases. Use a ball the same size as what is used as "the Earth" to represent Venus so the students can experiment with phases for this planet. This is a simple but powerful activity which directly addresses common misconceptions that students have about the Moon.

Investigation 4.1b: Understanding the Motions of Stars and Constellations Across the Sky

If possible, assign this as a nighttime activity. The students will time the appearance of a bright star approximately every five days for a two- to three-week interval. After recording the time for several observations, they can calculate the average difference. The students should determine that their object rises about 4 minutes later each night. The number that the students calculate using this difference is the true rotational period of the Earth. (The rotational period of the Earth is also called a sidereal day; this will be discussed later in the celestial sphere activity.) We use 24 hours for one day/night period and do not deal with the four-minute difference on a daily basis. Instead, it is compensated for by adding an extra day to the calendar and calling that calendar year a leap year. The direction of the apparent star movement is from East to West, and the angle of rising depends upon your latitude. If you are unable to use the nighttime sky, give the students the task of trying to recreate sky motions involving star and constellation motions within the classroom. The students who can use the night sky can then compare their results with the classroom recreations.

Core Activity 4.2: Using a Quadrant to Measure the Motion of the Moon, Stars, and Sun Across the Sky

Students construct their own quadrants to measure the altitude and angular separation of celestial objects. A template for the quadrant is included in the student section. They will also need straws, string, scissors, and small weights such as washers. Three activities are included which allow the students to make observations over long periods of time, enter their data in tables, and use the data to answer questions. There are many other types of observations; the three included are only a representative sampling. If your students are familiar with graphing, they can construct graphs of the observed motions. One example is the activity using Polaris and two stars in Ursa Major. A graph of the movement of these three stars would describe a straight line for Polaris, a steep slope for the star farther away from Polaris, and a more gradual slope for the star closer to Polaris. You may wish to discuss with your students factors that affect the accuracy of the quadrant, and challenge older students to develop and construct a better, more accurate, design. A template for a quadrant is included within the student activity. Two students need to work together for the best results: one student to locate the object and one to hold the string and determine the angle. **NOTE:** The student section tells them **NEVER** to look at the Sun through the straw on the quadrant. They are to point the straw towards the Sun and look at the circle that appears on their hand or on a piece of paper. Students should be reminded to never look at the Sun, either with the unaided eye or through sunglasses, or with binoculars or telescope, as the UV rays from the Sun will permanently damage the eye. An interesting video, “The Sun Dagger,” shows how the Anasazi used the Sun to mark the solstices. (See Resource List for details.)

RESOURCE

Core Activity 4.3: Why Constellations Appear in Different Places in the Sky at Different Times of the Year

This is a simple, highly visual activity, which reinforces the concepts of rotation and revolution. Students can be required to take into account the clockwise rotation of the Earth, cardinal directions, and degrees of movement each month of the Earth around the Sun (~30). Simple drawings of the constellations can be replaced by any art form, and the Zodiac can be Western or from any other culture. The related mythologies can also be discussed. Have students hold up large sheets of paper, or cloth sheets to hide the six constellations not visible during the daytime sky. It would be more realistic if they were painted or dyed blue to represent the sky. (A diagram is included in the student pages.)

Ask students why stars cannot be seen during the day. You may also have a student represent the Moon in this model, and ask when stars can be seen from the Moon. Most people think that, seen from the Moon, the sky is black and filled with stars; however, the far side alternately faces towards and away from the Sun, and the side facing Earth is affected by “Earthshine,” which washes out part of the sky.

NOTE: An excellent visual model to help students understand star motions is a clear plastic umbrella with some of the major constellations glued to the inside in approximately correct positions. (The cloth from an old umbrella can be removed and replaced with clear plastic.)

Poster Page: Abe Lincoln and the Almanac Trial

Besides the examples listed on the poster page, there are several historical associations with lunar phenomena, such as the first voyage of Christopher Columbus, and the Boston Tea Party. Also, bright comets and solar eclipses have influenced the course of history on several occasions. Solar eclipses played a part in the lives of Einstein, Nat Turner, and the Shawnee Indian Tecumseh, among others; comets were influential in the lives of Montezuma and the Aztecs, the Roman emperor Nero, and the Millerite cult in the northeastern United States. Paintings, poems, and stories, which include astronomical phenomena can be checked for accuracy, just as with the Almanac Trial. There are several software programs which will accurately display all aspects of the night sky for any date and time. (See Resource List for details.)

RESOURCE

Core Activity 4.4: The Rotating Earth and the Sun's Apparent Motion Across the Sky

a. Shadow Stick Astronomy

This activity demonstrates that the Sun casts shadows of different lengths and different angles as the Earth rotates. Measurements need to be taken every half hour all day long, so choose a sunny day. The activity can either take place outdoors, or indoors next to a large south-facing window. Students can use the quadrants they made for Activity 4.2 above.

If they have not constructed quadrants, they can measure the length of the shadow and divide that number by the measured length of the stick. The angle equal to the resulting ratio can be read from Table 4.1, included within the student activity. More advanced students can use right-angle trigonometry instead of using the table.

b. Shadows on a Sphere

This activity is an excellent reinforcement of the shadow stick activity above. You can use ready-made spheres or make your own by cutting off the round bottoms of 2-liter plastic soda bottles. The only difficulty with this method is that sometimes the glue used to put the dark flat bottom onto the round clear bottom is difficult to remove. Inexpensive plastic spheres can be obtained from Project Star (see Resource List for details) or from party-supply or novelty stores. RESOURCE

The results are a reflection of the shadow stick activity above—high in the middle and low on the ends, whereas the shadow stick reveals a dip in the middle and high ends. The shape of the shadows on the sphere is an excellent lead-in to the celestial sphere. Redoing this activity throughout the year will show students the changing altitude of the Sun. If a student is going on vacation in a different latitude, they could perform this activity, or the previous activity using the gnomon (described in Part (a) above), and compare their results with local graphs for the same day.

Core Activity 4.5: Constellation Plots

This activity uses the HOA constellations (Ursa Major, Cepheus, Cassiopeia, Cygnus, Auriga) and Ursa Minor. All except Cygnus and Auriga are circumpolar for upper latitudes in the northern hemisphere. You may wish to have your students plot constellations which correlate with your location. If so, sky charts for your area can be found via software programs (see Resource List for details), local colleges and universities, and local amateur astronomy groups. Plotting on polar coordinate paper is a graphing activity rarely encountered in the classroom, and the celestial sphere coordinate system is reinforced by using the right ascension and declination coordinates to plot constellations. *A completed graph is included to show what the student plots should look like.*

RESOURCE

Variable stars, by convention, are designated on maps by an open circle. If your students are going to observe the variable star in Cepheus (delta Cephei), this is an excellent introduction to the location of this constellation. Cygnus includes W Cyg, another AAVSO (the American Association of Variable Star Observers) program variable star. Also W Cyg is the variable star used in the slide set which the students will be using to learn the skill of magnitude estimation in Chapter 6. This is an excellent lead-in activity for Activity 4.6, which follows. Chapter 5 addresses some of the mythologies corresponding with these constellations. Some extension activities follow, and there are many more possibilities.

Extension Activities

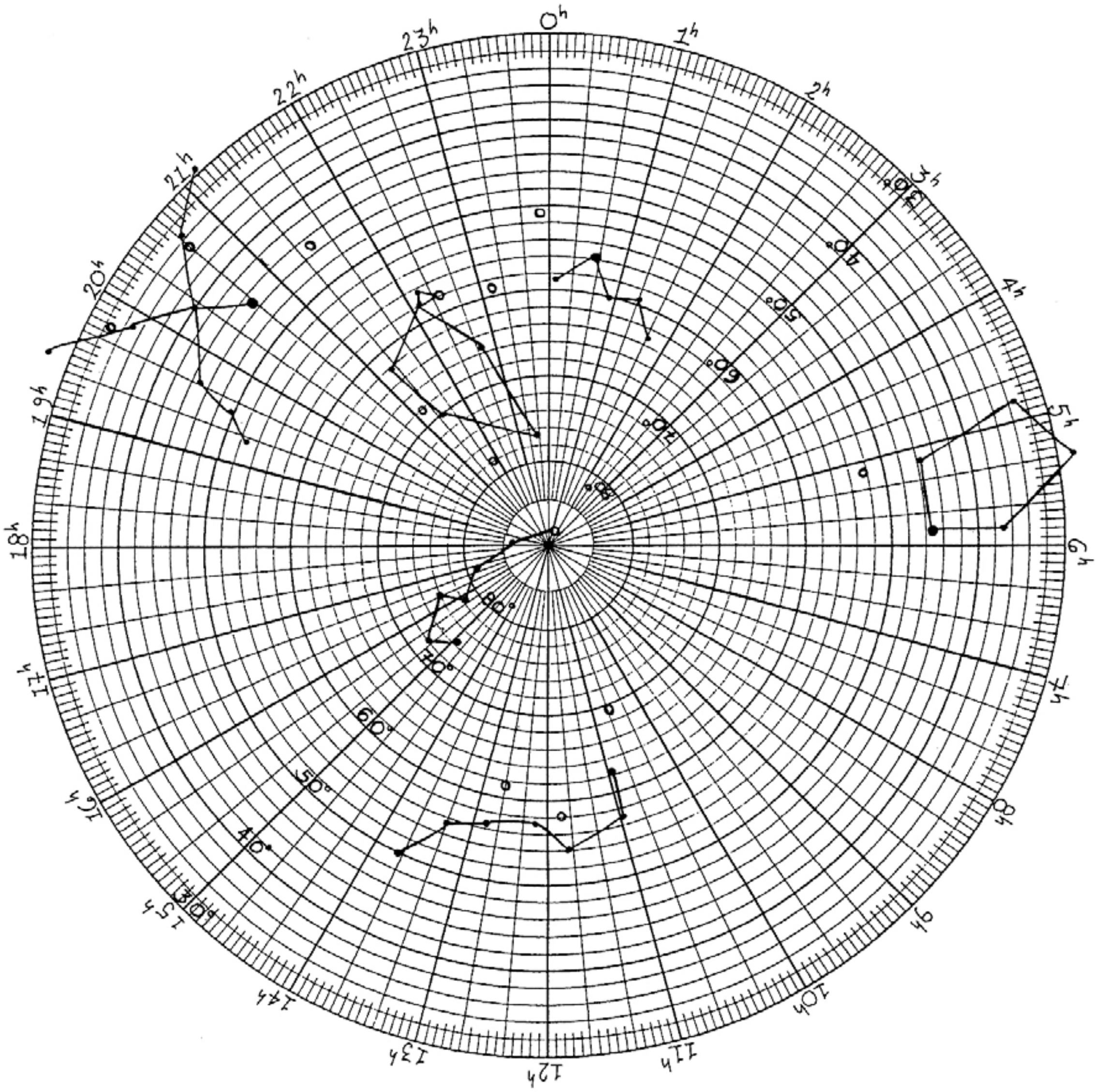
1. The stars have strange-sounding names. What are the origins of these names? Who named the stars? What do the names mean in the English language? What is the historical significance of the origin of the names for the stars? Why do different cultures have different names for the stars?

2. What is the mythology associated with these constellations for the different cultures, i.e., Greek, Roman, Chinese, American Indian, and so on? What are the advantages of using our own mythologies? Why don't we use the myths of other cultures?

3. Construct a polar coordinate graph for the circumpolar constellations for someone living south of –40 degrees latitude in the southern hemisphere.

4. At what latitudes on the Earth are there no circumpolar constellations? At these latitudes, how can one determine North by looking at the sky?

5. Would you still see the same constellation patterns that we see from Earth from the Moon? Mars? Pluto? The nearest star? (The stars are so far away that the same patterns would be visible from the nearest stars.)



Completed graph for the Core Activity 4.5 constellation plot

Activity 4.6: Plotting the Actual Positions of the Planets

This activity reinforces the concepts of rotation and the celestial coordinate system, especially right ascension (RA). Students construct a model by plotting the current celestial coordinates of the Sun and planets. It is a “geocentric” model, using polar coordinate paper with the Earth located in the center, and requires a sophisticated understanding of celestial motions for students to be successful in answering the questions. The right ascension and declination coordinates of the Sun and planets can be obtained from several astronomical handbooks or other sources, such as *Sky & Telescope.* This activity can be accomplished on paper; however, if the outermost planets are to be plotted, the paper must have a minimum diameter of 60 cm (2 ft).

If a paper model is used (scale of 1 cm = 1 AU), the scale indicated in the activity and the right ascension (RA) coordinates of the planets and Sun are used. However, if this becomes an outdoor activity, declination can also be plotted. The outdoor approach is strongly recommended, using a scale of 1 meter = 1 AU. The students can cut out lengths of string proportional to the planets’ distance from Earth. Then a marker or picture can be placed at these positions to represent the planets or the Sun. Elevated markers can be used to represent declination coordinates (keeping in mind that the declinations vary from –23.5 degrees to +23.5 degrees).

Distances to Mercury and Venus may be larger than 1 AU if their positions are on the other side of the Sun with respect to Earth (superior conjunction). The students can take turns standing in the center on the “Earth” and rotating counterclockwise to determine night and day, and note visibility of constellations and planets. The constellations can also be placed around the outside of the planets, with Pisces located at 0 hours right ascension. This activity helps students understand the concept of a sidereal day.

Explanations about why Mercury and Venus are visible only during morning or early evening can be made by noting that the RA of the two are always close to the Sun; as the Earth rotates counterclockwise, they are either able to see the two planets just after they lose sight of the Sun (dusk), just before they see the Sun (dawn), or not at all if the planets are too close to the Sun.

NOTE: This is a *geocentric* model of the Solar System, with Earth located at its center. It represents the positions of planets and the Sun as they appear to observers on Earth. Once again, you can reinforce both the usefulness and distortions of models with your students.

Poster Page: Astrology or Astronomy? (Horoscopes and Precession)

You can use this issue as a stimulus for discussions and research, as pseudoscience affects important aspects of our culture. Horoscopes are one of the most prolific an enduring aspects of pseudoscience. The general population tends to confuse astrology with astronomy. It is mistakenly thought that astronomy evolved from astrology, and that therefore astrology is a true science. Actually, judicial astrology did not appear until 600 BC, long after the Babylonian astronomers had developed their astronomical tables, calendars, star charts, and lunar eclipse theory. Astrology became a dominant force during the reign of the Roman Empire, and with the fall of the empire, astrology ended in the Western world for 500 years. The Arabs acquired astrology when they took over Greek culture; astrology had developed in Greece during the Hellenistic period.

In the early medieval period, astrology was reintroduced to the Western world through Arabic medicine. Astrology also became associated with alchemy, mathematics, and astronomy. Astrology had a devastating influence on medicine of the time, for physicians ceased making diagnoses from symptoms and case histories and relied on horoscopes to tell them why the patient was ill, what drugs to prescribe, and the favorable time to apply remedies. Astrology also hindered the development of chemistry. It was only after alchemy had been purged of astrology and other superstitions that chemistry became a separate discipline. Furthermore, astronomers were often forced to earn their living by astrology while carrying on legitimate science as best they could.

Interestingly, astrology has flourished in periods of high scientific development rather than in low periods, and also during periods when religion and philosophy were unpopular. The Reformation and Roman Catholic Counter-Reformation were instrumental in ending the power of astrology in the 1600's. In our time, astrology has again become popular with the public, and recent polls show that 60% of the population believes in some aspect of pseudoscientific phenomena.

Students can take opinion surveys, and also survey the existing materials associated with astrology. Horoscopes and psychic hotlines have targeted females as their primary audience. These articles appear in women's magazines, not *Field and Stream,* and women's magazines are found in grocery stores, drug stores, and doctor's offices—places that women visit more frequently than do men. Why are the articles found in women's magazines? Is it because astrology deals with emotional issues and women are perceived as being more emotional than men? Is it because women as a group are not as scientifically literate as men? What psychological issues cause people to believe such fraudulence? What needs are being fulfilled by these flights from reality? These issues are complex and interrelated and have no simple answers.

NOTE: Another major claim of astrologers is that planetary alignments are important events and can influence humanity. Activity 4.6 shows that the planets all have different inclinations to the plane of the Solar System, and that even though sometimes the planets *seem* to be aligned, in actuality they are not.

Chapter 5: Introducing the Variable Star Astronomy Constellations

Petroglyph in 9 Mile Canyon, Utah depicting Coyote Scattering the Stars in the Sky

Introduction

Early observers organized stars into easily recognizable patterns that resembled the objects, animals, and people important to their survival and religions. We now call these patterns constellations. From our perspective here on Earth, it appears that the stars in any given constellation are connected in some way, that they all occupy the same part of space, and are all the same distance from the Earth. However, in reality, most stars within constellations are up to several light- years away from each other. An example is the Big Dipper. Alkaid, the star at the end of the handle, is 100 light-years away from Earth. The next handle star is actually two stars that appear very close together. The brighter star, Mizar, is 78 light-years away from Earth, and Alcor is 81 light- years away. Mizar and Alcor are 3 light-years apart in the sky, a distance of 27 trillion kilometers, and Alkaid and Mizar are 22 light-years apart, a distance of 198 trillion kilometers! An exception is the Pleiades, the "Seven Sisters" asterism. The Pleiades is an open cluster, a group of stars born together in the same stellar nursery and now slowly drifting apart.

The constellation names and boundaries we recognize today were officially established in 1930 by the International Astronomical Union (IAU). The entire sky is now partitioned into 88 irregularly-shaped pieces, and one constellation is assigned to each piece.

The history of constellations, of who named them, and when, is full of myth, rumor, and ambiguity. Surviving records are contradictory and few, and open to interpretation. Some can be traced back to a particular origin; others only hint at their beginnings. Decoding the past—through rock art, paintings, stone monuments, and oral story-telling traditions that were written down only in more recent times—is a challenging task. Such artifacts and ancient records can be translated or interpreted in a variety of ways. Sometimes one constellation has one story, sometimes it has several stories or myths.

Sometimes the same story can have several different variations. We will never know the actual sources of many constellation names and myths: they are lost in time. However, one possible key to the antiquity of a particular constellation with its associated mythology is the amount of sky which it covers—with the earliest occupying large portions of the sky, and more recent constellations occupying smaller portions, though this is not always the case.

A few bright stars associated with every constellation have been named by different cultures. European and Arabic culture names were assigned by early Roman, Babylonian, Greek, Sumerian, and Arab astronomers. Other cultures, such as Native American and Chinese, have their own names for the same stars. Star names have meanings rooted deep within each culture; however, it would be bewildering if different cultures continued to use their own names for the same star. The inconsistency of star names necessitated the development of a more systematic method of nomenclature, or naming. We now use brightness as the criterion to label stars within any given constellation. The star with the brightest apparent magnitude in each constellation is named "alpha," followed by the possessive form of the Latin name for the constellation; the second brightest, "beta," the third brightest, "gamma," and so on down through the Greek alphabet. For example, the most common name for the brightest star in the constellation Auriga is "Capella," although it has been given other names by other cultures. The scientific name of this star is "alpha Aurigae" or just "α Aurigae," or even "“α Aur" ("Aur" being the abbreviation for Auriga). This system of naming stars is the one most commonly used by astronomers. Since there are more stars in a constellation than letters in the Greek alphabet, several different naming systems take over after the last Greek letter is used. One of these systems will be presented in Chapter 6. Below are listed the possessive forms and abbreviations for the constellations presented in this chapter, and the Greek alphabet for your reference in naming the stars within the constellations.

CONSTELLATIONS

Name	Possessive Form	Abbreviation
Auriga	Aurigae	Aur
Cassiopeia	Cassiopeiae	Cas
Cepheus	Cephei	Cep
Cygnus	Cygni	Cyg
Ursa Major	Ursa Majoris	UMa

GREEK ALPHABET

α alpha	η eta	ν nu	τ tau
β beta	θ theta	ξ xi	υ upsilon
γ gamma	ι iota	ο omicron	φ phi
δ delta	κ kappa	π pi	χ chi
ε epsilon	λ lambda	ρ rho	ψ psi
ζ zeta	μ mu	σ sigma	ω omega

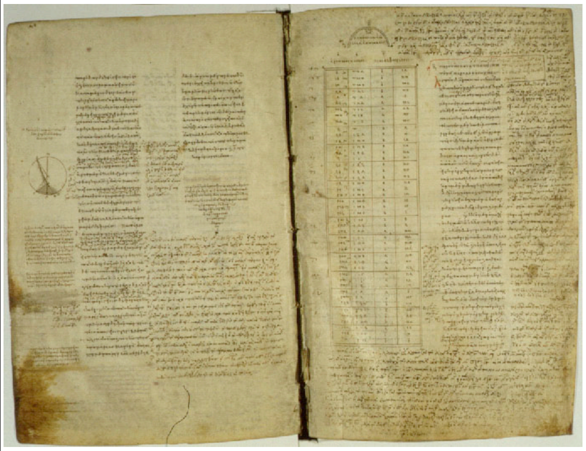
Whatever the mythologies associated with the constellations, the stars and other celestial objects they contain are very real. For centuries, the constellations have guided ancient explorers and travelers over unknown lands and uncharted seas. We are now going to investigate five constellations: Auriga, the Charioteer; Ursa Major, the Big Bear(containing the famous asterism the Big Dipper); Cygnus, the Swan; Cepheus, the King of Ethiopia; and Cassiopeia, the Queen of Ethiopia. They are full of spectacular sights and contain many interesting objects, including variable stars. Many contain deep-sky objects, such as globular clusters, galaxies, and nebulae, which come in different sizes, brightnesses, shapes, and colors.

Investigation 5.1: The Magnitude of Stars in a Constellation

Your instructor will show you a slide of one of the constellations mentioned in the introduction. Sketch the main stars of the constellation pattern, remembering that the brighter the star, the larger the point. Label the brightest star as alpha, then continue ranking the brightness of the stars using the sequence of Greek letters in the table above. How does your diagram compare with those of the rest of the class? Does everyone agree on the ranking of magnitude?

How Do You Keep Track of the Stars?

You may live under city lights and can see only a few of the brightest stars, or you may live farther out in the suburbs or in the country and can see hundreds of stars. If you are in a place that has very dark skies, you may be able to see, with your unaided eye, about 3000 individual stars from where you stand. Use binoculars or a small telescope, and the number increases to many thousands of stars. How do you keep track of what you have seen? What happens when you start recording what you see in the sky?



Part of a manuscript copy of Ptolemy's star catalogue in The Almagest.

The more information you collect about the stars, the more you need to keep it arranged in some systematic way. When you make a list of the stars you observe, together with your observations about the star, you are compiling information. Once your list grows to more than a few hundred items, it becomes, properly speaking, a *catalogue*.

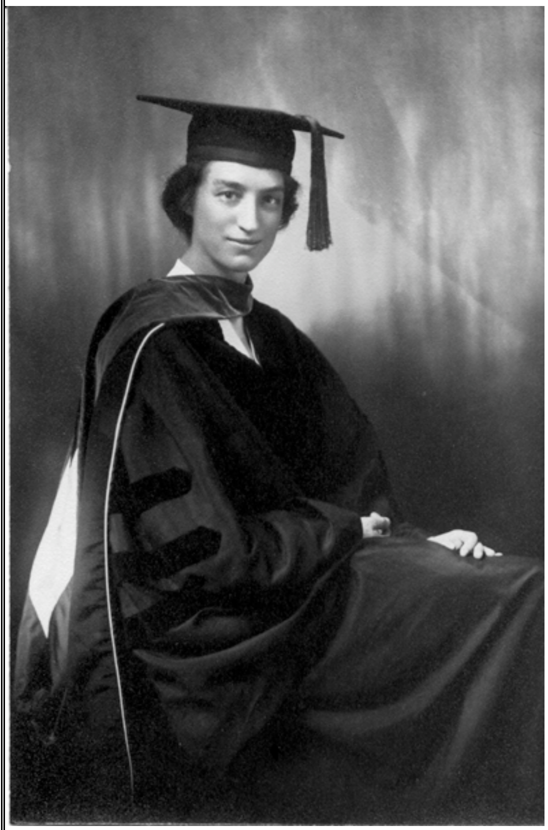
Observers of the night sky have been compiling catalogues for a long time. The earliest known star catalogue was compiled by Hipparchus; however, it is known only by references to it in other sources. The catalogue itself has long since been lost or destroyed. An early formal star catalogue is contained in a work by Claudius Ptolemaeus (Ptolemy) of Alexandria, called *The Almagest* (which is Arabic for *The Greatest*), compiled in about 140 A.D. Ptolemy's *Catalogue of Stars* comprised two of *The Almagest's* thirteen volumes. In the catalogue, Ptolemy gives the positions of 1,022 stars having magnitudes from 1 to 6.

Ptolemy's catalogue is important because it is the oldest account of positions of stars that is accurate enough to compare to modern Part of a manuscript copy of observations. Ptolemy's *Catalogue of Stars* was the only reliable and widely used listing of star positions from 138 until 1602 when Tycho Brahe published a catalogue of his own observations.

Catalogues are fundamental to the work of astronomy. Without catalogues, astronomers would very quickly lose track of new information about the stars, and would have to spend many hours in the library just to find one small fact about a star. Star catalogues are vital tools for the astronomer, and yet compiling a catalogue is work that most astronomers would shun. Researching and compiling the information of others is unglamorous work compared to searching for new stars or planets through a powerful telescope, or thinking of new theories about the origin of the universe.

HD	HR	HIP	Name	RA 2000.0 (h m s)	Dec 2000.0 (d m s)	Parallax (mas)	V	Spectral type and luminosity class
1461	72	1499	–	00 18 42	−08 03 11	42.67	6.46	G5 V
157 089	–	84 905	–	17 21 07	+01 26 35	25.88	6.95	G0–2 V
162 396	6649	87 523	–	17 52 53	−41 59 48	30.55	6.20	F8 IV–V
189 567	7644	98 959	–	20 05 33	−67 19 15	56.45	6.07	G3 V
193 307	7766	100 412	–	20 21 41	−49 59 58	30.84	6.27	G0 V
196 755	7896	101 916	κ Del	20 39 08	+10 05 10	33.27	5.05	G5 IV
210 918	8477	109 821	–	22 14 39	−41 22 54	45.19	6.23	G5 V

Information on 7 of the 9110 stars listed in The Bright Star Catalogue, fourth revised edition, published in 1982. This was the last edition of this catalogue to be published in the form of a book. Subsequent editions are now published primarily in a computerized format.



E. Dorrit Hoffleit, Ph.D. Radcliffe, 1938

Dr. Dorrit Hoffleit is one astronomer who has not shunned the difficult, tedious, and time-consuming work of compiling star catalogues. Even though she has been officially retired from her position as senior research astronomer at the Yale University Observatory for 20 years now, she continues to do a great deal of research work in astronomy. Dr. Hoffleit's 90th birthday was marked by the completion of the fourth edition of the *Yale Catalogue of Stellar Parallaxes.* This is a two-volume compilation of 15,994 parallaxes that were computed for 8,112 stars. These measurements are important because they tell how far away these stars are. As collaborator with Dr. William F. van Altena, the primary author, and Dr. John Truen-liang Lee, Dr. Hoffleit was mainly responsible for conducting the literature searches necessary to ensure not only that the material included in the catalogue was up to date, but also that conflicts in information about these stars would be noted and resolved.

Dr. Hoffleit was also responsible for the third, fourth, and fifth revised editions of *The Bright Star Catalogue.* Her work on these catalogues spans a period of about 30 years. *The Bright Star Catalogue* is one of the most frequently consulted reference works in astronomy. The fifth edition of *The Bright Star Catalogue* was revised on magnetic tape at the Astronomical Data Center (ADS), Goddard Space Flight Center, Greenbelt, Maryland. This catalogue, and many others like it, are now made available primarily in machine-readable form such as magnetic tapes or computer diskettes. The trend over the last 10 years or so has been to digitize as many of these standard reference catalogues as possible. This monumental task is mainly the responsibility of two agencies, the Astronomical Data Systems (ADS) of NASA, and the Centre de Données Astronomiques de Strasbourg (CDS) in France.

"These are not flashy things," van Altena says about Hoffleit's work with star catalogues. "They deal with the fundamental nature of stars. They're things that astronomy needs to make any progress toward the future. It's all very fine to make grand theories about the age, size, and origin of the universe, but if you don't know how bright or massive stars are then you're building on a house of cards."

Dorrit Hoffleit was born in Alabama in 1907. She wanted to study astronomy after she saw the collision of two meteorites in the sky above her home in rural Western Pennsylvania. She went to college at Radcliffe, and earned her doctorate in astronomy from Harvard University. Dr. Hoffleit spent the first half of her 70-year astronomy career at Harvard College Observatory, and the second half at Yale University Observatory. From 1956 to 1978 she also directed the Maria Mitchell Observatory in Nantucket, Massachusetts, where she established a program to help young women and men discover research opportunities in astronomy. Dr. Hoffleit's astronomy work is wide-ranging. The study of variable stars is one of her specialties: she discovered 500 variable stars in the constellation Sagittarius. She has also studied, researched, and written about meteors and comets, spectroscopy, astrometry, astronomy education, and history of astronomy. Her passion for work in the field of her choice eclipses the more ordinary things in her life. "Work for the work's sake," Dr. Dorrit Hoffleit says, "and it will become a part of you."

Investigation 5.2: A Study of the Constellation Auriga, the Charioteer

Auriga is a perfect example of how confusing the mythologies of a constellation can be. There are varying myths concerning the constellation itself, as well as separate stories about its brightest star, Capella. Auriga is represented as a man who has one foot on the constellation Taurus, the Bull. The star that is the tip of the left horn of Taurus is shared with Auriga. Auriga is holding a set of reins in his right hand, and carrying a female goat with two kids in his left arm. Capella represents the female goat. Since the myth surrounding Capella is so different from that of Auriga, it is possible that one myth was superimposed over another, more ancient, myth. The depiction of Auriga as a shepherd might have originated as a myth in its own right.

Auriga is associated with two separate charioteers in Greek mythology. One is the coachman Erichthonius, represented as half-man and half-serpent, who is credited as the inventor of the chariot. Another story is about Myrtilos, the charioteer of Oenomaus, the king of Elis. The king had a beautiful daughter who had many suitors. The king, however, was fearful of a prophecy that foretold of his death at the hands of his future son-in-law. He vowed his daughter would never marry. Keeping his vow a secret from his daughter, Oenomaus did not simply forbid her to wed. Instead, he said that any suitor had to win his daughter by beating him in a chariot race. If they lost, "off with their head!" The king had the best horses in the country, and Myrtilos kept them in excellent condition. The king's daughter, whose name was Hippodameia, knew that Myrtilos was secretly in love with her. The next contestant was Pelos, with whom Hippodameia was in love. Hippodameia asked Myrtilos as a favor to loosen the bolts on the king's chariot during the next contest. This Myrtilos readily agreed to, hoping that the princess would be grateful enough to accept him as her husband. When the loosened bolts came out of the king's chariot, the king was killed. Myrtilos tried to run away with Hippodameia, but Pelos caught up with him and cast him into the sea to his death.

Another Roman myth claims that Auriga, the crippled son of the goddess Minerva and the blacksmith god Vulcan, who was also lame, invented the chariot to make it easier for himself and his father to move around. The other gods then honored Auriga for this improved form of transportation by placing him in the sky with a wagon whip in his hand.

Capella may be associated with the Roman story of the goat named Amaltheia who provided Jupiter with milk on the island of Crete. Jupiter was the son of Saturn and Rhea, and Rhea had taken Jupiter to the island to protect him from his father, who had been known to devour his children. Several other stories equate the rising of Capella with the beginning of the new year. Capella was called Dilgan in Sumerian mythology and Dendera by the Egyptians, and both of these cultures marked their new years with the rising of Capella. Because the start of a new year is usually associated with the vernal equinox, Capella and Taurus could have been utilized as calendars in this fashion from approximately 3700 to 1700 BC. The Egyptians saw Dendera as a mummified cat carried by a man wearing feathers. In India, Capella was a god holding a string of pearls representing the changing lunar cycle.

The constellation Auriga is visible in the night sky of the Northern Hemisphere from December to February. Capella, alpha Aurigae, is actually a bright yellow double star system with a surface temperature that is the same as our Sun. It is located approximately 13 light-years from Earth. Apart from Capella and the other obvious bright stars which you drew in the previous activity, there are other interesting objects located within the constellation.

Your instructor will show you a slide of the constellation Auriga. There are some variable stars located within this constellation as well as in the other constellations in this chapter. One star that changes in brightness is epsilon Aurigae, located in the area of the goat's kids. This is not, however, a star that you want to watch through a complete cycle of change in brightness: Epsilon Aurigae is an eclipsing binary with a period of about 27 years. The supergiant being eclipsed is so large that the Sun and entire Solar System would fit inside the star! Epsilon Aurigae is 625 light-years from Earth.

Within Auriga are three open clusters of stars, M36, M37, and M38. Open clusters are groups of stars which were born together within the same cloud of gas and dust, have the same motions in space, and are held together by mutual gravitation. They have similar ages and chemical compositions, but may differ in mass, magnitude, and temperature. The open clusters are usually found in narrow regions within the spiral arms of our galaxy. The highest concentration is found along the Milky Way in the constellation Sagittarius, the direction of the galactic center.

The Aurigid meteor shower originates from the direction of Auriga, close to Capella. This shower peaks in mid-September.

Investigation 5.3: A Study of the Constellation Ursa Major, the Big Bear

Seven stars form the Big Dipper, the well-known asterism in Ursa Major, which is among the oldest recognized patterns in the sky. It is a prominent pattern of bright stars and is circumpolar for mid-northern to polar latitudes in the Northern Hemisphere. Interestingly, although the pattern represents a variety of objects to many cultures—a plow, wagon, coffin, skunk, camel, shark, canoe, bushel, sickle, even a hog's jaw—several cultures share myths concerning a bear. Archaeological evidence suggests that the stories about this constellation may date back to the Ice Age when ancient people could cross over the Bering Strait to North America. At that time, cultures in both Siberia and Alaska shared a common heritage. It is even thought possible that the constellation actually got its name 50,000 years ago when a paleolithic bear cult existed.

A recurring theme that runs through mythology is the kinship of bears and humans. Bears can lumber along on all fours, or stand up on their hind feet and gesture with their front paws. Ursa Major, in its travels throughout the heavens, constantly changes from quadrupedal to bipedal positions, seeming to run along on all fours nearest the horizon and then rising to its hind feet to begin the ascent back into the sky. There have been many fairy tales and fantasies written about people taking the form of bears. In some cultures bears are regarded as gods.

One story about the Big Bear is shared by the Micmac Indians of Nova Scotia and the Iroquois Indians along the St. Lawrence seaway. In this story, the quadrangle of the dipper represents a bear who is pursued by seven hunters; the three closest hunters are the handle of the dipper. As autumn approaches, the four farthest hunters dip below the horizon and abandon the hunt, leaving the closest three hunters to chase the bear. The hunters are all named after birds. The closest hunter to the bear is named Robin, the second closest is Chickadee, and the third is Moose Bird. Chickadee is carrying the pot in which the bear will be cooked. The second star in the handle is actually two stars, called Mizar and Alcor, which represent Chickadee and the pot. In autumn, as the bear attempts to stand up on two legs, Robin wounds the bear with an arrow. The wounded bear sprays blood on Robin, who shakes himself and in the process colors the leaves of the forest red; some blood stains Robin and he is henceforth called Robin Redbreast. The bear is eaten,and the skeleton remains traveling through the sky on its back during winter. During the following spring a new bear leaves the den and the eternal hunt resumes once more.

A Roman myth involves both bears, Ursa Major and Ursa Minor. A beautiful maiden, Callisto, hunting in the forest, grew tired and laid down to rest. The god Jupiter noticed her and was smitten with her beauty. Jupiter's wife, Juno, became extremely jealous of Callisto. Some time later, Juno discovered that Callisto had given birth to a son and decided that Jupiter must have been the father. To punish her, Juno changed Callisto into a bear so she would no longer be beautiful. Callisto's son, called Arcas, was adopted and grew up to be a hunter, while Callisto continued to live in the forest. One day Callisto saw Arcas and was so overjoyed at seeing her son that she rushed up to him, forgetting she was a bear. Arcas thought he was being attacked and shot an arrow at Callisto. Jupiter saw the arrow and stopped it from hitting Callisto. To save Callisto and her son from further damage from Juno, Jupiter changed Arcas into a bear also, grabbed them both by their tails, and swung them both into the heavens so they could live peacefully among the stars. The strength of the throw caused the short stubby tails of the bears to become elongated. Juno was even angrier at Jupiter and managed to exact still more revenge on poor Callisto and Arcas. She went to the gods of the sea and forbade them to let the two bears wade in their waters or streams on their long and endless journey around the pole star.

An Arab myth associates this asterism with a funeral. The quadrangle represents a coffin and the three handle stars are people following the coffin and mourning. The middle star (really the two stars Mizar and Alcor) represents the daughter and son of al-Naash, the man in the coffin, who has been murdered by al-Jadi, the pole star. Other cultures, too, relate funeral processions to the Big Dipper.

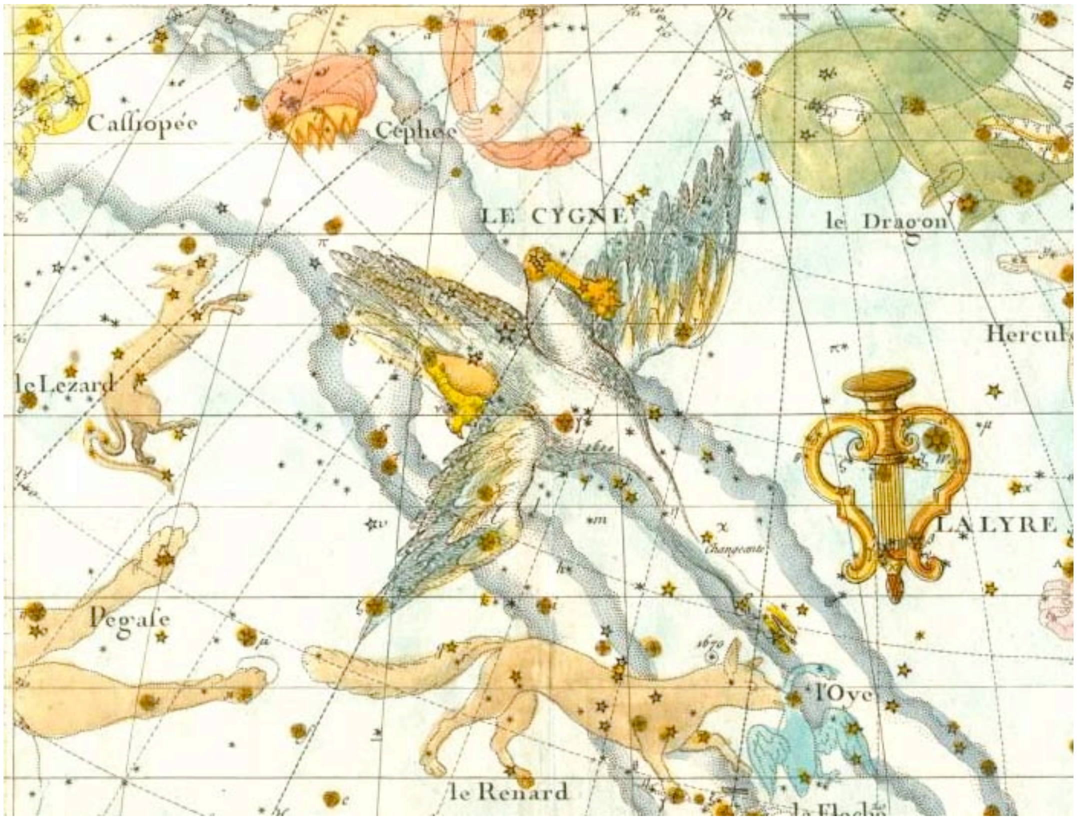
You will be shown a slide of the Big Dipper. After you have become familiar with some of the celestial objects located within this star pattern, you will be able to view it in the night sky with a greater appreciation. Even though Ursa Major is a circumpolar constellation for the Northern Hemisphere, from March through May it is at its highest point in the sky, away from the horizon and light pollution, and easier to observe.

Look at the middle star in the handle of the Big Dipper and you will be able to see the two stars named Mizar and Alcor. Even though they look close together and seem to be touching each other, they are not. They are at different distances from us and just happen to fall in the same line of sight. The term for this apparent closeness from our perspective is *optical double*. During World War I and World War II, these stars were used for testing vision. Anyone who could distinguish the two stars with the unaided eye was given a rating of 20/20. If you look at Mizar and Alcor through a telescope, you will see that Mizar is part of a double star system and has a companion star. So what on casual glance seems to be a single star in this small piece of the sky is in reality three stars.

Within this constellation are several spiral galaxies similar to our own Milky Way, such as M81, M101, and M108. Each one of these galaxies contains billions of stars, and exhibits unique and interesting characteristics. Ursa Major also contains several variable stars. In 1993, an amateur variable star observer from Spain found a bright supernova visible from the Northern Hemisphere. Just think! The information from the death of this star journeyed through space for millions of years before falling through the lens of a telescope into the eye of an observer. Until that moment, no one knew the star had died. Since then, scientists have continued to study this part of the sky to understand more about supernovae.

In Ursa Major, we also encounter M97, a planetary nebula. Contrary to intuition, a planetary nebula has nothing to do with planets. Some stars going through the dying process are not massive enough to explode into supernovae; they just shed some of the outer layers of their atmosphere into clouds of gas that surround them. When viewed through a telescope, the planetary nebula looks like an oval or circular disk with a blue-green central star. M97 is called the “Owl Nebula” because it resembles an owl. The planetary nebula stage represents a brief period in the history of a star. After the nebula dissipates, the highly compressed core will become a white dwarf about the size of the Earth. Our Sun will begin to die in about five billion years; after passing through the red giant stage, it too will become a white dwarf. Perhaps it will throw off a planetary nebula which the inhabitants of some other planet will see, and name after something its shape resembles in their culture.

Investigation 5.4: A Study of the Constellation Cygnus, the Swan



The origin of Cygnus is quite ancient. It has most often been represented as some sort of a bird. In Mesopotamia it was called the Bird of the Forest. It has also been referred to as a duck or a hen. The constellation was named Cygnus by Eratosthenes, a Greek who is famous for calculating the circumference of the Earth by measuring the length of a shadow cast by the Sun on a day when he knew its rays shone directly into the bottom of a well several kilometers away.

One of the myths involved with the swan is the story of Cycnus and his friend Phaethon, the mortal son of the Sun god Helios. Phaethon took the Sun Chariot for a ride and lost control, endangering the gods with his recklessness, and setting fires when the thundering horses came too close to Earth. Jupiter threw Phaethon out of the chariot, and he fell into the river Eridanus and drowned. Cycnus was devastated by his friend's death and dove into the river again and again, collecting the bones of Phaethon so he could bury them. Cycnus did not want his friend to roam as a ghost through the Upperworld for all eternity, but to rest in peace in the Underworld. Jupiter was moved by this devotion and rewarded Cycnus by changing him into a swan, and renaming him Cygnus. Cygnus was placed in the Milky Way, which represents the path of destruction of the Sun Chariot.

Another famous legend is that one day Jupiter saw a beautiful maiden by the name of Leda bathing in the river Eridanus, and changed himself into a swan so he could get close to her without being recognized. When Leda stroked the beautiful swan, Jupiter changed back into his own form.

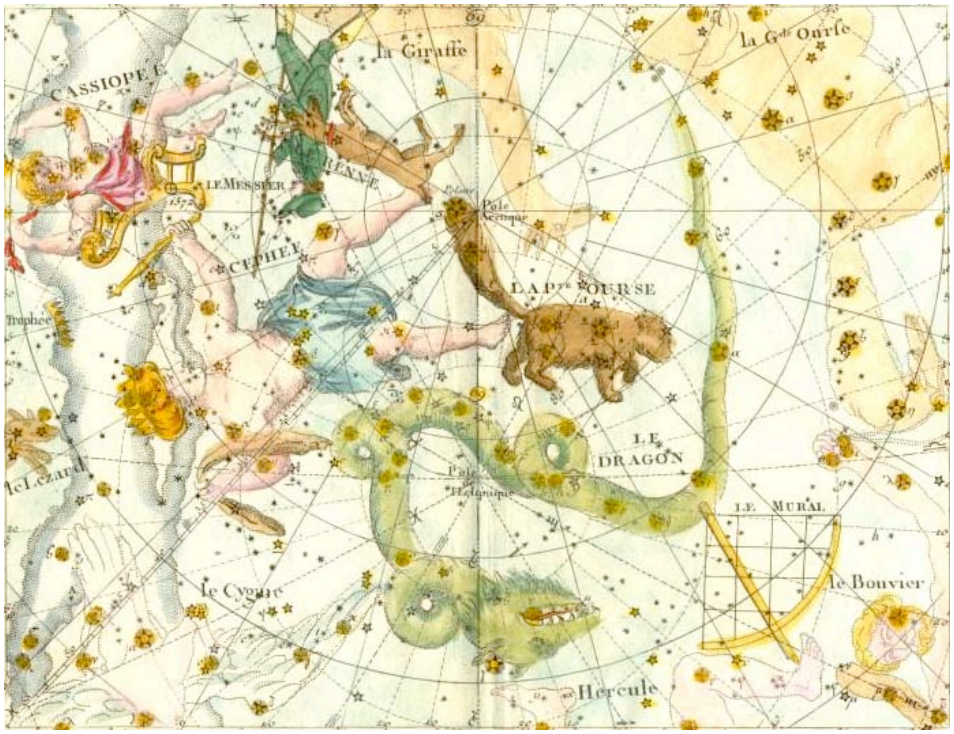
Cygnus is also called the Northern Cross. This name has its origins in the early 1600's. The Northern Cross represents the Cross of Calvary. Many Christians considered it significant that the orientation of the cross on Christmas Eve is upright and prominent on the horizon before it begins its annual descent and disappears from the night sky.

You will be shown a slide of Cygnus, which is visible high in the summer sky. Its brightest star, alpha Cygni, also known as Deneb, is one of the bright stars making up the asterism of the Summer Triangle. Deneb is actually a double star system and is approximately 1500 light-years away. Beta Cygni, or Albireo, is a red supergiant and also part of a binary star system which is easily visible with binoculars or a small telescope. Cygnus lies within the Milky Way and is therefore quite dense with stars. One of its stars, 61 Cygni, was the first star whose distance was measured from Earth using parallax. Parallax is the apparent change in position of a star against the background pattern of stars. You can see this same phenomenon by holding your arm straight out in front of you with your thumb up. Look at your thumb with your left eye closed. Then look at your thumb with your right eye closed. Notice that your thumb appears to "jump" relative to whatever is behind it: this is parallax. This measurement was accomplished in 1837 by Friedrich Wilhelm Bessel, a Prussian astronomer. 61 Cygni is 11 light-years away.

Variable stars abound in this part of the sky. We will study one in particular, W Cygni, which exhibits a large change in magnitude on a regular basis. There are several different types of variable stars. Some that are not very regular are called *semiregular variables*. *Eruptive* or *cataclysmic variables* suddenly change their brightness when either their thermonuclear processes become unstable, or atmospheric material from companion stars fall onto their surface. These semiregular and eruptive stars offer no clue as to when they will brighten. It is fascinating to study these stars, and amateur astronomers play an important role in observing them.

Near the tail of Cygnus is a bright cloud of partially obscured gases called the North American Nebula. The Veil Nebula, the remnant of an ancient supernovae explosion, is also in Cygnus. Cygnus is the home to two open clusters, M29 and M39, and to the Cygnid meteor shower, which seems to emanate from Deneb in July and August.

Investigation 5.5: A Study of Cepheus, the King of Ethiopia

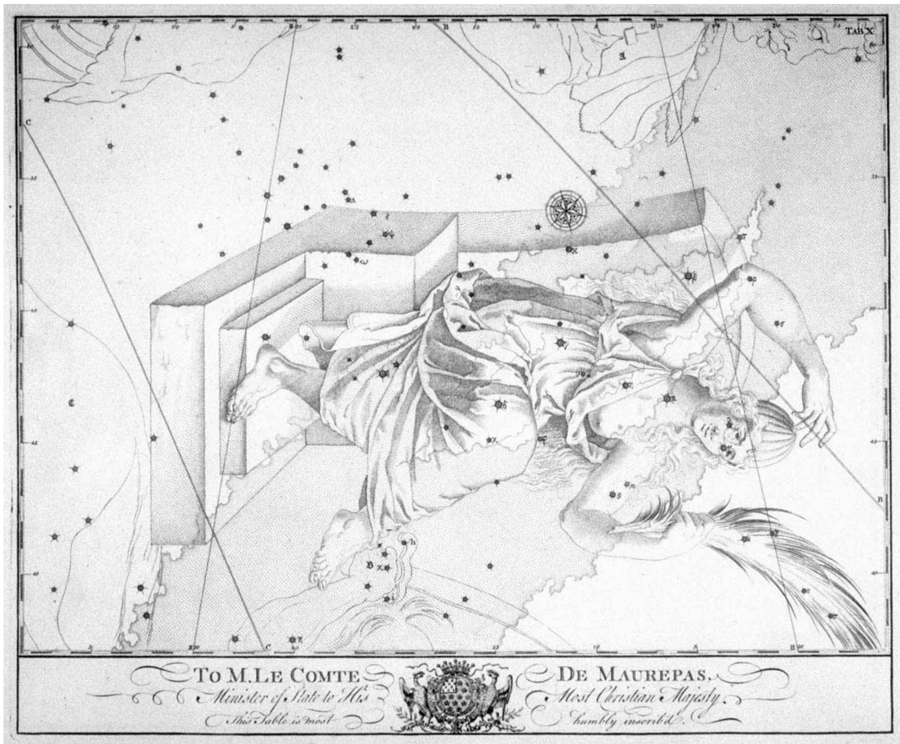


This region of the sky has usually been associated with a king. Arab astronomers called this constellation al-Multafab, the Blazing One, while in China it was called the Secret Throne of the Five Emperors. In Greek mythology Cepheus was an Argonaut and the king of Ethiopia, husband to Cassiopeia. Cepheus and Cassiopeia had a daughter named Andromeda. These three are associated with two other constellations, Perseus and Pegasus the Flying Horse. Because Cassiopeia, vain and boastful, insulted the gods, Cepheus was ordered to sacrifice Andromeda as a punishment. However, Andromeda was saved by Perseus and Pegasus.

Cepheus himself constantly circles the pole, with his feet in the constellation of Ursa Minor, one foot close to Polaris. This is a dark region of the sky, and it is difficult to see any pattern in the stars making up Cepheus that might suggest a king. Not much is known about King Cepheus, and in classical times *all* lands to the south—including India and Arabia—were called Ethiopia, so exactly where his kingdom was located is not known.

Your instructor will show you a slide of Cepheus, a circumpolar constellation in the Northern Hemisphere and most easily visible in the summer and fall. The variable star delta Cephei is one of the most interesting objects in this constellation. It is visible with the unaided eye and its period of change in brightness is only a few days. This is one of the first stars that new variable star observers study. You will also learn how to locate this variable star, record and analyze the data, and learn why this star and others of this type show variability. Delta Cephei is the prototype of all Cepheid variables, which are used by astrophysicists in determining the distance to stars and the age of the universe.

Investigation 5.6: A Study of the Constellation Cassiopeia, the Queen of Ethiopia



Cassiopeia's vanity about her beauty angered Poseidon, who unleashed the monster Cetus and demanded the sacrifice of her daughter, Andromeda. As an eternal reminder that mere mortals should not compare themselves to the gods, Cassiopeia travels constantly around the North Celestial Pole. When she is above the North Pole, the constellation has the shape of an M; when below the North Pole the M turns upside down into a W shape. During this time Cassiopeia is decidedly in danger of falling off her throne and must hang on to avoid falling out of the sky. Because the gods sometimes show temperance in their anger, for part of the year Cassiopeia is allowed to sit upright and temporarily regain her dignity. Cassiopeia, Cepheus, and Andromeda are often portrayed as being dark-skinned, since they were said to come from Ethiopia.

The five stars that make up the W shape were seen as the fingertips of a hand by the ancient Arabs, and was referred to as Tinted Hand, Dyed Hand, or Broad Hand Dyed with Henna. Arab women sometimes dyed their nails, hands, and feet with henna at weddings and ceremonies, and sometimes as protection from the heat. After the arrival of Muhammad, the Tinted Hand became the hand of Fatima, daughter of Muhammad, covered in blood. The Arabs have also called this constellation the Lady on the Throne.

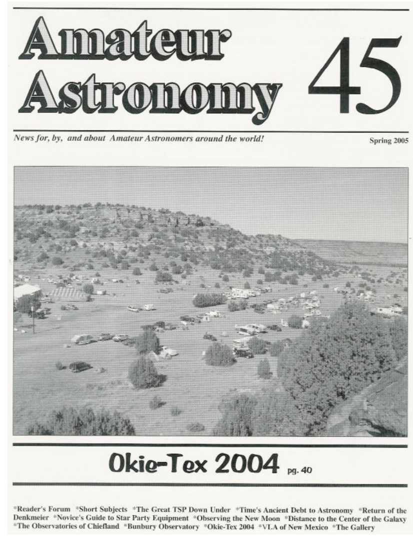
Some minor myths in this part of the world see a camel which incorporates both Cepheus and Cassiopeia, and sometimes Perseus.

Chinese mythology associates this constellation with a chariot, the transportation used by those visiting the court of the emperor. It is also associated with two great charioteers, Wang-liang and Tsaou-fou. To natives of the Marshall Islands, a huge porpoise lives in this part of the sky which incorporates four constellations, including Cassiopeia, which is the tail of the porpoise. Siberians see five reindeer, and Laplanders see the antlers of a moose.

You will be shown a slide of the constellation Cassiopeia. It is circumpolar in the Northern Hemisphere, and in the fall it is high in the sky and least affected by light pollution. Part of this constellation lies within the Milky Way.

Cassiopeia has its own share of bright open clusters, including M52 and M103, as well as a planetary nebula called the Bubble Nebula. It also includes a large number of various types of variable stars.

Astronomy is for Everybody



The stars are free. Anyone can look up at the night sky and see the stars. And with a little knowledge, practice, and skill, anyone can begin to understand what is happening out there. People have been doing this for thousands of years. Some of the most important discoveries about the stars and planets were made by individuals who began by looking up and wondering.

But the individual's observations cannot be of much use if they are made in isolation. To look up and wonder about the stars and not talk about these questions with others is like someone writing wonderful poems and putting them away in a desk drawer. What we see and think about is just the beginning: our observations will mean something if we can make them known to others who have a similar interest in the stars. This works in both directions: something may be happening in the stars that you yourself have not seen, but you learn about it because others have seen the event and have communicated it to you.

There are amateur astronomy groups everywhere in the world. This happens anywhere two or more people get together to talk about what they see in the stars and how they go about it. An astronomy group can be two, or a few, or dozens, hundreds, or thousands of people who are eager to share what they know with others.

Professional astronomers have come to depend on these formal and informal networks of amateur astronomers' clubs and organizations. Most unpredictable events-like the appearance of novae and supernovae, comets, meteor and meteorite events, and sudden brightening or fading of stars-would go unnoticed by the professional astronomer if it were not for the nightly observations communicated by amateurs to their astronomy groups.

The Story of the AAVSO

...and it is a fact that only by the observation of variable stars can the amateur turn his modest equipment to practical use, and further to any great extent the pursuit of knowledge in its application to the noblest of the sciences.

- William Tyler Olcott, 1911, Co-Founder of the AAVSO

In 1909, William Tyler Olcott, a lawyer, amateur astronomer, and the author of *The Field Book of the Stars* and other popular astronomy books, heard Harvard College Observatory Director Edward C. Pickering give a talk and exhibit some light curves and charts of variable stars. This fascinated Olcott, who immediately afterwards wrote Pickering to ask if he could become a variable star observer. In response, Harvard assistant and variable star observer Leon Campbell went to Norwich, Connecticut, where Olcott lived, "to initiate Mr. Olcott in the art of variable star observing." On February 2, 1910, Olcott "succeeded in locating the field of Omicron Ceti" and made his first official variable star observation. From that date on, Olcott regularly sent observations The AAVSO annual meeting, 1917. to Professor Pickering at the Harvard College Observatory.

The March 1911 issue of *Popular Astronomy* carried an article by Olcott entitled, "Variable Star Work for the Amateur with Small Telescopes." Events then moved quickly and in the November issue, Olcott, signing himself "Corresponding Sec'y," announced that an organization had been formed by co-founder E.C. Pickering and himself, W.T. Olcott, and he suggested as its name, The American Association of

Variable Star Observers (AAVSO). He listed six people who had indicated their desire to cooperate, and included a list of 71 stars he himself had been observing. Thus, with the founding of the AAVSO, Pickering's dream of advocating variable star observations by amateurs became a reality.

The AAVSO annual meeting, 1917.

By the end of its first year, over 6000 observations of 175 stars from 19 observers were published in *Popular Astronomy*. As participation increased, Olcott wanted to become better acquainted with the observers; he wrote, "I wanted to see what they look like." On April 8, 1914, the first informal meeting was arranged in a restaurant on 42nd Street in New York.

In November 1915, the first official meeting of the AAVSO took place at Harvard College Observatory, and the twelve observers who attended met co-founder Edward Pickering and Leon Campbell, the first recorder.

At its meeting in November 1917, the group decided to be organized formally and in October 1918, the AAVSO was incorporated under the laws of the Commonwealth of Massachusetts.

The organization grew steadily in membership. By 1950, observers were contributing data at a rate of about 55,000 variable star observations each year. In 1957, with the launching of the Russian satellite *Sputnik*, the activities of the Association also took off. AAVSO's first involvement with space research took place with participation in satellite tracking. The involvement of observers in professional research increased. The International Astronomical Union, at its General Assembly in 1961, suggested that the AAVSO become the central repository for all variable star observations.

In 1962, the two-millionth observation was received from Leslie C. Peltier, only 16 years after the one-millionth in 1946. Increasing numbers of requests came from professional astronomers for AAVSO data as special interest in flare stars, eclipsing binaries, cataclysmic and nebular variables, and extragalactic supernovae accelerated, and observations of variable stars expanded beyond the optical region of the electromagnetic spectrum with instruments aboard balloons and planes.

The participation of AAVSO observers was sought by space researchers in almost all of the satellite and ground-based observing runs on cataclysmic variables. AAVSO's collaboration through observers' closely monitoring target stars and alerting astronomers to observed activity played an important role in the success of these sophisticated observing programs. Requests from astronomers for AAVSO data increased exponentially during the 1970s and 1980s, and the vital contributions of AAVSO observers were acknowledged in numerous astronomical papers.

Today the AAVSO stands strong on the foundation built by such giants as William Tyler Olcott, Edward C. Pickering, Leon Campbell, and the thousands of dedicated members and observers. The Association is international in scope with its 1300 members worldwide, and, with over 15 million observations, has the largest data bank on variable stars in the world. The AAVSO is rightly a source of pride to all who have contributed to what it is today.

The AAVSO annual meeting, 1996.

SPACE TALK

Variable stars—stars that change in brightness—are divided into two major groups, **extrinsic** and **intrinsic**. Extrinsic variables change in brightness either by the eclipse of one star by another, or by the effects of stellar rotation. An **eclipsing binary** system is created when two stars are orbiting each other and one star, from our perspective on Earth, happens to pass in front of and then behind the other star. These magnitude changes result in a distinct pattern that is observable. One example of an eclipsing binary is beta Persei (Algol).

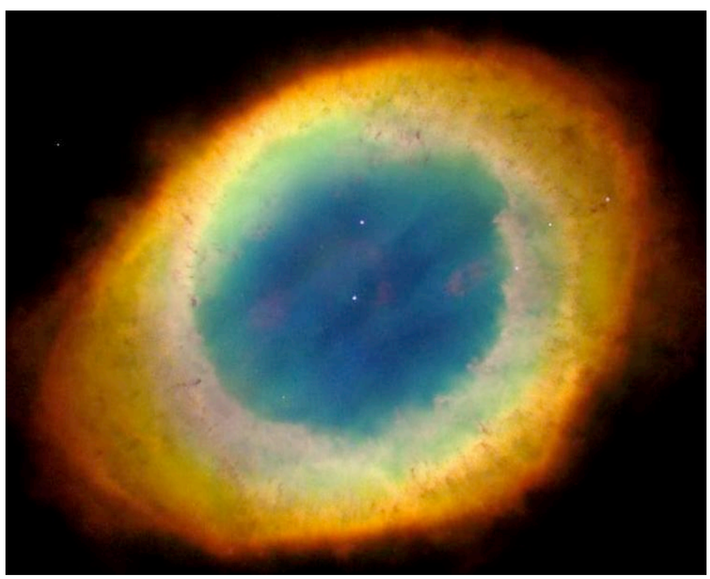
Our own Sun is also a type of extrinsic variable star! Our Sun has sunspots, which are related to its magnetic activity. Sometimes there is a large area of dark sunspots on the Sun's surface, and as the Sun rotates, the sunspots rotate also—sometimes facing the Earth, sometimes facing away from the Earth. The Sun's apparent magnitude increases when the sunspots face away from the Earth, and decreases when the sunspots face towards the Earth. Other stars also have "starspots" that produce changes in magnitude as they rotate.

Intrinsic variable stars change in magnitude due to internal physical changes that cause them to periodically brighten and fade. **Pulsating variables** are one type of intrinsic variable star. Stars are luminous balls of gas held in equilibrium by two forces operating in opposing directions—gravitational force directed towards the center of mass of the star, and **radiation pressure** from the thermonuclear fusion process directed from the core towards the surface of the star. Some stars pulsate because a small imbalance between these two forces stops the star from reaching equilibrium. When the star pulsates, it expands past its equilibrium point until the expansion is slowed and reversed by the force of gravity, and it then contracts. It then overshoots its equilibrium point again until the contraction is slowed and reversed by the increased radiation pressure from the core of the star. The mechanism responsible for the continued pulsations or oscillations of most variable stars does not originate in the core, but in regions of instability within the stellar atmosphere. Delta Cephei, in the constellation Cepheus, belongs to one type of pulsating variable called Cepheid variables.

Another group of intrinsic variable stars are **eruptive variables**. There are several types of eruptive variables which undergo eruptions or explosions instead of pulsations. The most spectacular are the catastrophic **supernovae** explosions which occur in massive dying stars. The thermonuclear fusion process in stellar cores consists of the conversion of hydrogen to helium. When the supply of hydrogen is exhausted, the nuclear fires start to sputter and the star begins to collapse. The resulting stages of **stellar evolution** for dying stars depends upon their initial mass. When stars twice as massive as our Sun begin to die, heavier and heavier elements are produced by the fusion process. Eventually, in the most massive stars, the nuclear fires burn so hot during the final stages of collapse that iron starts to fuse. All elements lighter than iron produce energy during the fusion process, but iron consumes energy. When iron starts to fuse, the stage is set for complete disaster—nothing can stop the total destruction of the star. In a fraction of a second, a star that has existed for millions of years will cease to exist in the visible universe. The unimaginably violent death leaves behind nebulae—beautiful layers of atmospheric material thrown from the surface during the explosion—sometimes the only evidence of the star's previous existence. Supernovae display light increases of 20 magnitudes or more and can outshine all other stars in a galaxy.

Betelgeuse (alpha Orionis) is a luminous red **supergiant** in the constellation Orion. It is a **semiregular variable** star, having periods of regular pulsations interrupted by periods of irregular light variation. Betelgeuse is five times more massive than the Sun and is in a **binary system** with a 14th-magnitude companion star. Betelgeuse is 410 light-years away, and will eventually become a supernova. Here on Earth, we will not know of the destruction of Betelgeuse until 410 years after its core has evolved into a neutron star, leaving its atmospheric layers behind. Betelgeuse does not have enough mass to become a black hole.

Another example of eruptive variables are **novae**. Novae result from stars in two different evolutionary stages orbiting each other in close binary systems. For example, a star with its atmosphere bloated during the **red giant** stage may be orbiting a dense, hot **white dwarf**. The loosely-held outer atmospheres of a red giant sometimes whirl into a disk and spiral onto the surface of the more dense white dwarf, triggering nuclear reactions on the surface. The increase in brightness can range from 5 to 20 magnitudes. A white dwarf has an extremely dense carbon core, the end result of stellar evolution for low-mass stars like the Sun. Before the final collapse into the white dwarf stage, these stars go through a red giant phase, during which a **planetary nebula** is sometimes ejected from the star. The ejection of a planetary nebula is not as violent as a supernova explosion, and after approximately 50,000 years planetary nebulae become too thin and tenuous to be seen. In approximately 5 billion years, the Sun will evolve through a red giant phase and its bloated surface will extend beyond the orbit of Mars, incinerating the inner planets. It may eject a planetary nebula before settling down as a white dwarf, slowly radiating its heat energy into space. Eventually, with all its heat dissipated, the Sun will become a **black dwarf**, a cold dense chunk of carbon, still accompanied by its frozen planetary family.



M57, the Ring Nebula in the Constellation of Lyra (HSTsI)

Unit 3: OBSERVING VARIABLE STARS

Observing variable stars involves locating them within the constellation, learning how to estimate their changing magnitudes, and recording the information. Finding objects in the night sky depends upon our knowledge of the constellations. We use the constellations to identify celestial objects or events: the Leonid meteor shower, for example, seems to radiate from the constellation Leo; the Andromeda Galaxy is located within the Andromeda constellation; the Ring Nebula is found in the constellation Lyra. Variable stars are also located within constellations, though seldom as part of the prominent pattern or asterism. Chapter 5, “Introducing the Variable Star Astronomy Constellations,” introduces five constellations that contain variable stars from the AAVSO International Database; Chapter 6, “Measuring Variable Stars Visually,” utilizes VSA slides to help students learn the skill of estimating magnitudes; and Chapter 7, “Observing Stars in the Real Sky,” is central to the Variable Star Astronomy curriculum—observing and recording magnitude changes of variable stars in the real sky.

CONTENTS FOR UNIT 3

Core Activity 6.5: Collecting Your Own Data
Poster Page: Who Are the Amateur Astronomers?
Core Activity 6.6: Magnitude Estimation and Graphing With Slides (and/or prints)
Space Talk on Visual vs. Photoelectric Observational Data

CHAPTER 7: OBSERVING VARIABLE STARS IN THE REAL SKY

This chapter is the core of the Variable Star Astronomy curriculum, introducing students to the process of variable star research. Students will be able to systematically observe bright variable stars such as delta Cephei and W Cygni.

Poster Page: Starlight In Your Eyes
Poster Page: Occupational Hazards of Variable Star Observing
Core Activity 7.1: Observing Your First Variable Star—Delta Cephei
Poster Page: She Discovered How to Calculate the Distances to Galaxies
Activity 7.2: Observing the Variable Stars W Cygni and Chi Cygni
Space Talk on Cepheids

Relationship to National Science Standards and Benchmarks:

The *National Science Standards* states that performing investigations in order to develop understanding, ability, values of inquiry, and knowledge of science content promotes inquiry learning. This unit is an application of the fundamental concepts which underlie the *Unifying Concepts and Processes* and *Science as Inquiry* Content Standards: observing, recording and analyzing data, and communicating the results. Both regularities and irregularities within systems produce patterns that are understandable and predictable. Some changes can be directly observed but not directly measured, and mathematics is the essential tool for measuring such changes. Mathematical calculations such as circumference, finding the mean, precision and significant figures, and comparing data for two groups by representing their averages and spreads graphically are all computation and estimation essentials listed in *Benchmarks.* The unifying concepts and processes emphasized within this chapter are *Evidence, Models, Explanation and Change, Constancy,* and *Measurement.* Past and present study of variable stars has contributed significantly to our fundamental understanding of the origin of the universe. Progress has come from both advances in technology and the contributions of professional and amateur astronomers from all walks of life. This unit shows how historical and current scientific knowledge each influence the use of prevailing technology, and how results are interpreted and evaluated.

Chapter 5: Introducing the Variable Star Astronomy Constellations

Summary

Five constellations are presented in this chapter: Auriga, Ursa Major, Cygnus, Cepheus, and Cassiopeia. Auriga is a winter constellation and Cygnus is a summer constellation, and the rest are circumpolar in the Northern Hemisphere. Students will investigate the stars and other celestial objects in these constellations. They will also learn about some of the mythologies associated with them.

Terminology

binary system	extrinsic variable	planetary nebula	stellar evolution
black dwarf	intrinsic variable	pulsating variable	supergiant
cataclysmic	nova	radiation pressure	supernova
eclipsing binary	optical double	red giant	white dwarf
eruptive variable	parallax	semiregular variable	

Common Misconceptions

1. *The stars within the constellations are the same distance from the Earth.*
2. *The constellation is only the prominent pattern of stars, or asterism, usually associated with the constellation.*

Suggestions for the Poster Pages, Investigations, and Activities

Investigation 5.1: The Magnitude of Stars in a Constellation

Select one of the VSA slides for this activity. You may find it easiest to start with the "UMa #1" slide of the Big Dipper, followed by "Aur #1," "Cep #1," and "Cas #1." You may choose *not* to darken the room when showing the slides for the first time. This way, only the brightest stars are visible. This may make it easier for students who find the background scatter of stars distracting. Also, if your students live in areas with lots of light pollution, the slide will more closely represent what they actually see in the sky. Another way to reduce the background clutter of stars on the slides is to mask the projector lens with an "iris" made from an index card in which you have punched a hole. If any of your students are undecided about the ranking of magnitudes, then slightly blur the focus of the slide—you can then more clearly see the brightness of the stars that seem to be of the same magnitude. You may elect to have the students address more than one of these slides, depending upon their skill level.

Poster Page: How Do You Keep Track of the Stars? (Star Catalogues)

The history of star catalogues is interesting, from the earliest catalogue to the most recent. What stars were included? What information was given about them? How were their positions determined? How were their magnitudes determined? How many stars were recorded in each successive catalogue? Who produced the catalogues? How does the number of recorded stars correspond to the development and availability of technological instruments? Were there bad catalogues? How do we keep track of the positions of stars today? What organizations are responsible? What is the purpose of star catalogues? Why is it important to know exactly where a star is located?

Investigations 5.2–5.6

These activities are a brief presentation of some of the mythologies associated with the VSA constellations. Show the corresponding slide for each activity. The variable stars listed below are the same variable stars that the students plotted in Core Activity 4.5. Using the finder charts, see if your students can locate the variable stars on the slides, or at least find their general vicinity. In case your students have difficulty locating the constellation patterns on the slides, we have included with this manual a set of finder slides, on which the constellation outlines, some of the variables, and other major stars have been indicated. You may use these at your discretion to assist your students. (The finder slides are reproduced on the following six pages.)

Auriga—R Aur

Ursa Major—R UMa, S UMa, Z UMa

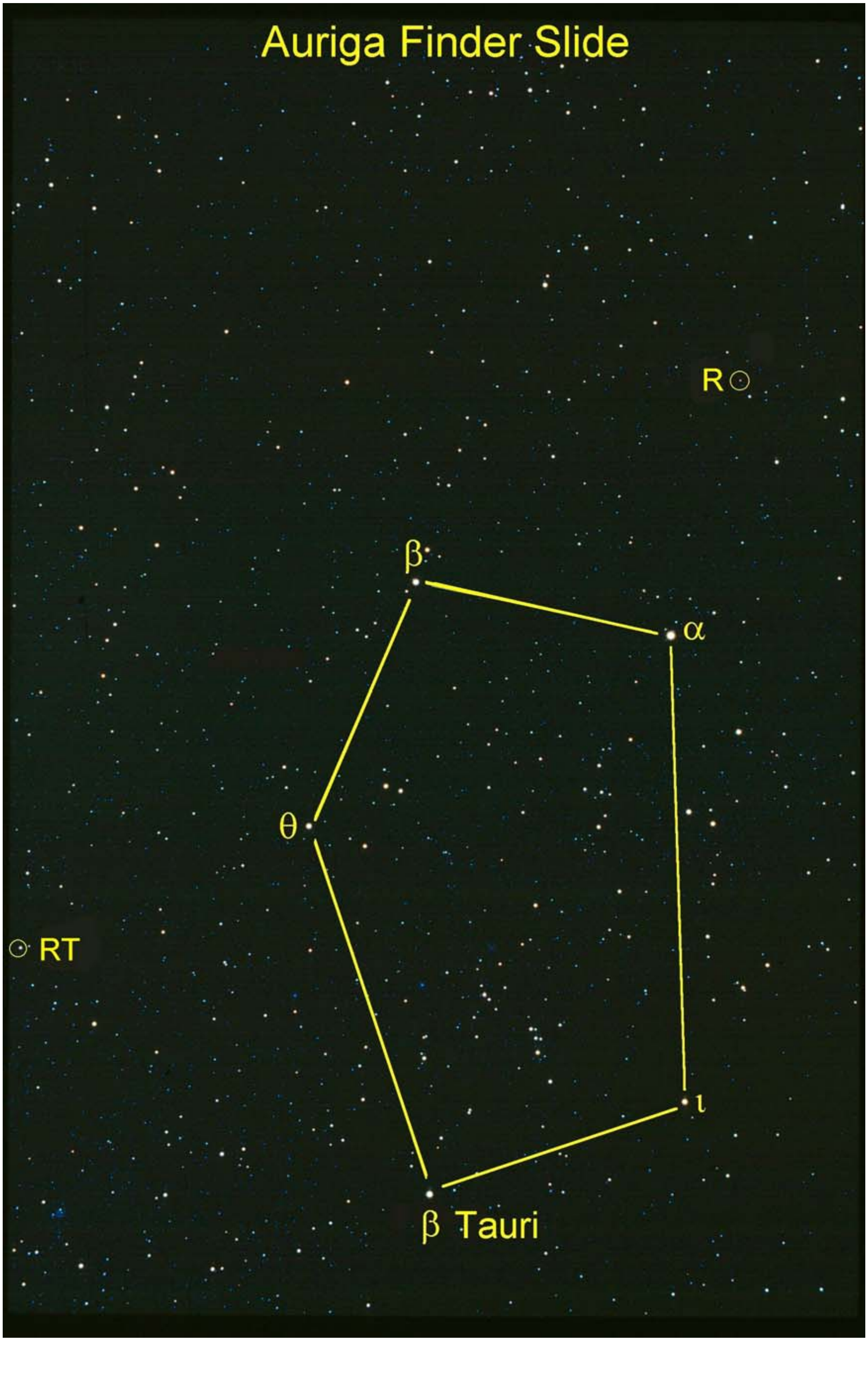
Cygnus—χ (chi) Cyg, W Cyg

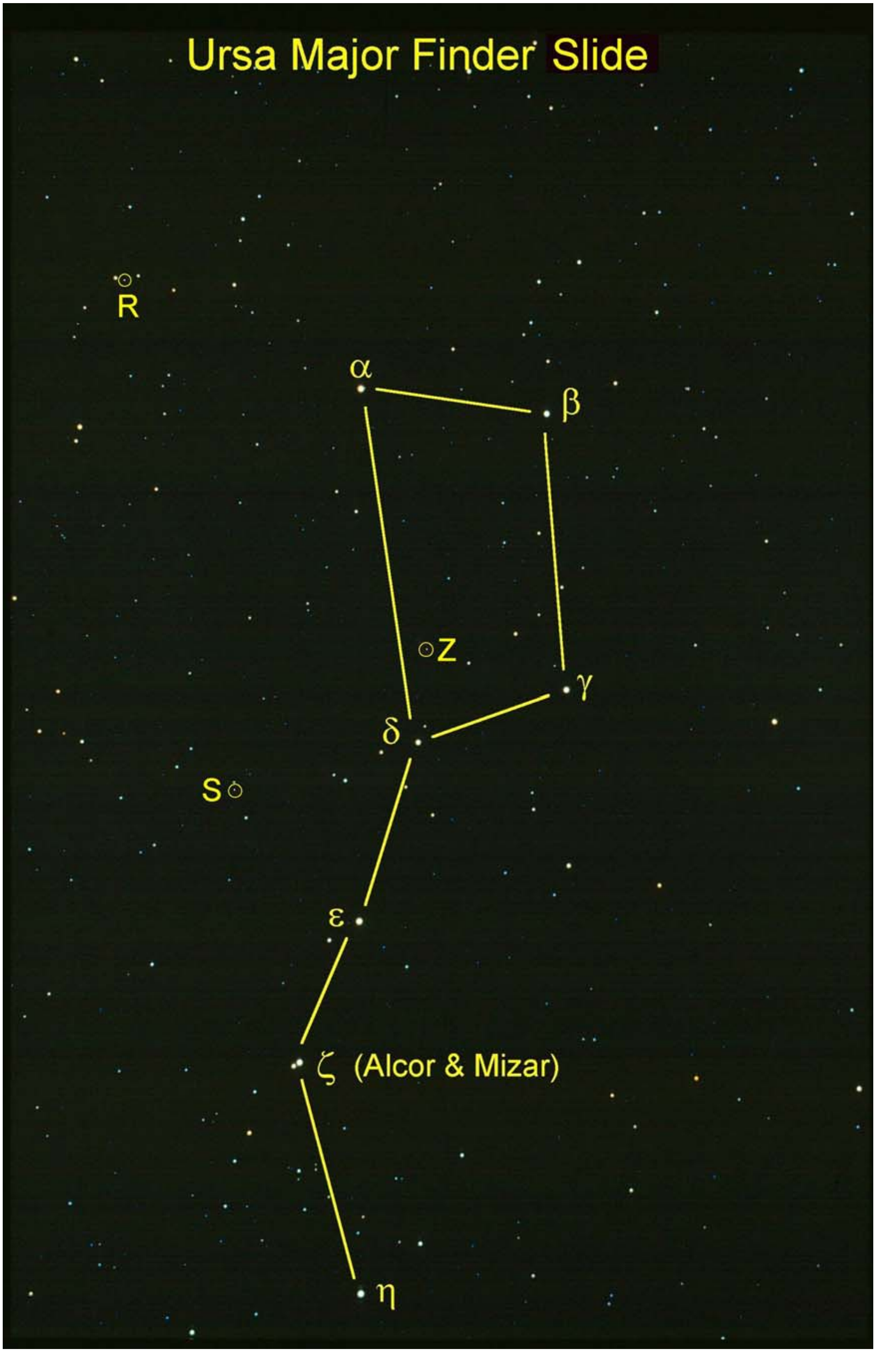
Cepheus—T Cep, S Cep

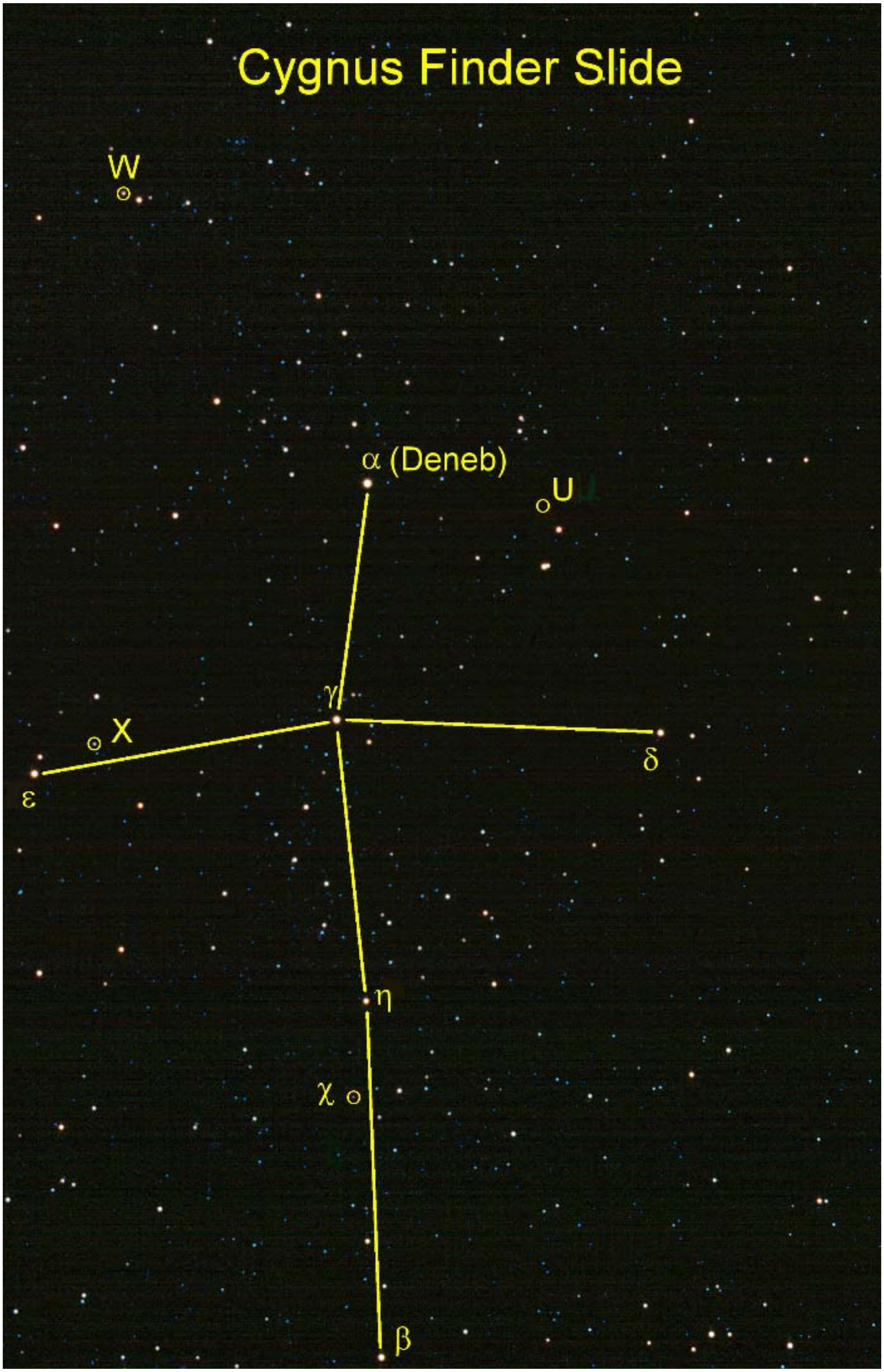
Cassiopeia—R Cas, V Cas

There are also several interesting deep sky objects within the constellations which cannot be visually detected. However, these objects are listed as points of interest in the student section. You may wish to obtain a slide set of deep sky objects so you can show them along with the VSA slides. (See details in the Resource List.) RESOURCE

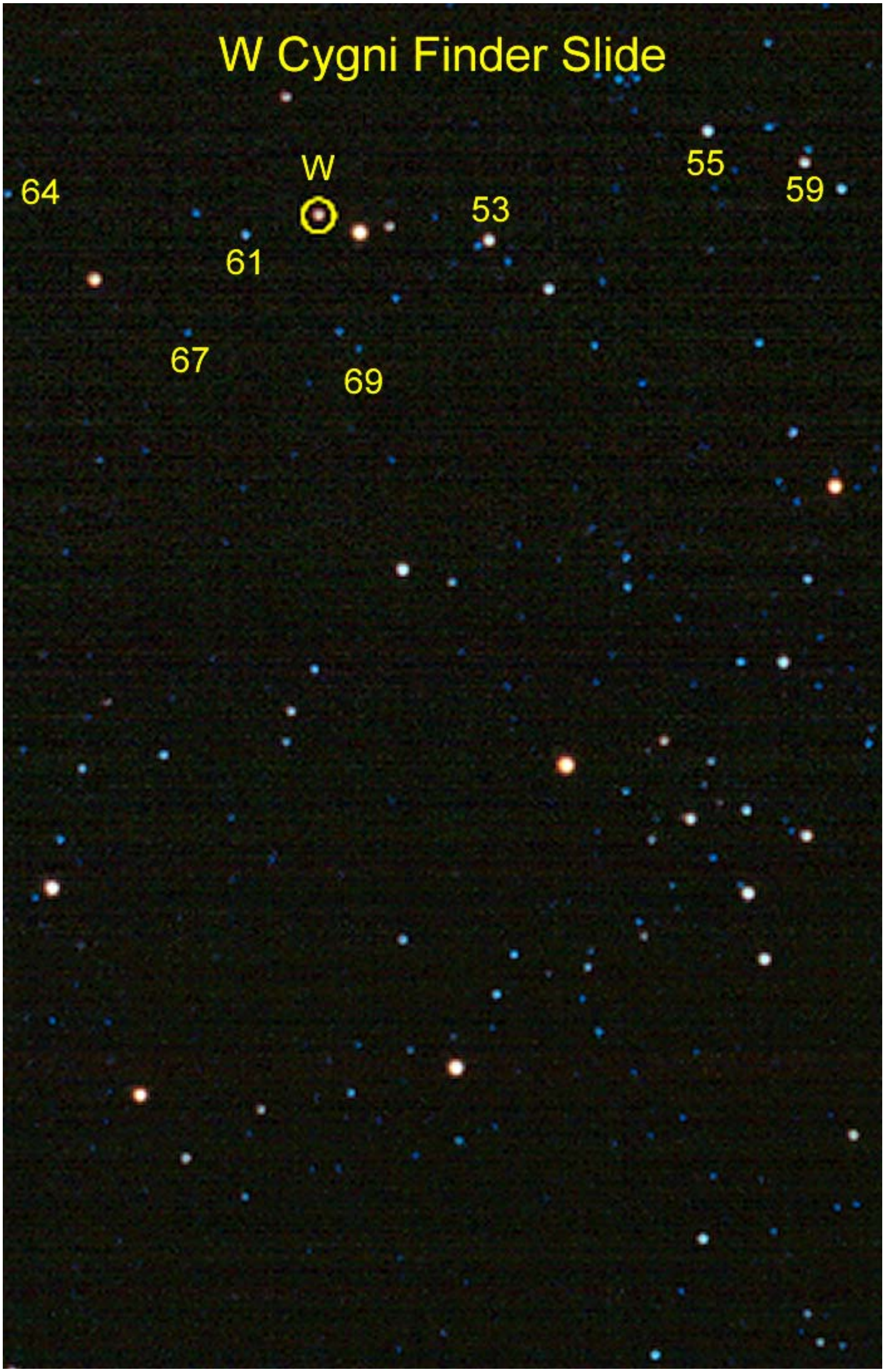
The concept of parallax is introduced on page 82 of the student section. A more detailed explanation is found in Poster Page 11.1.

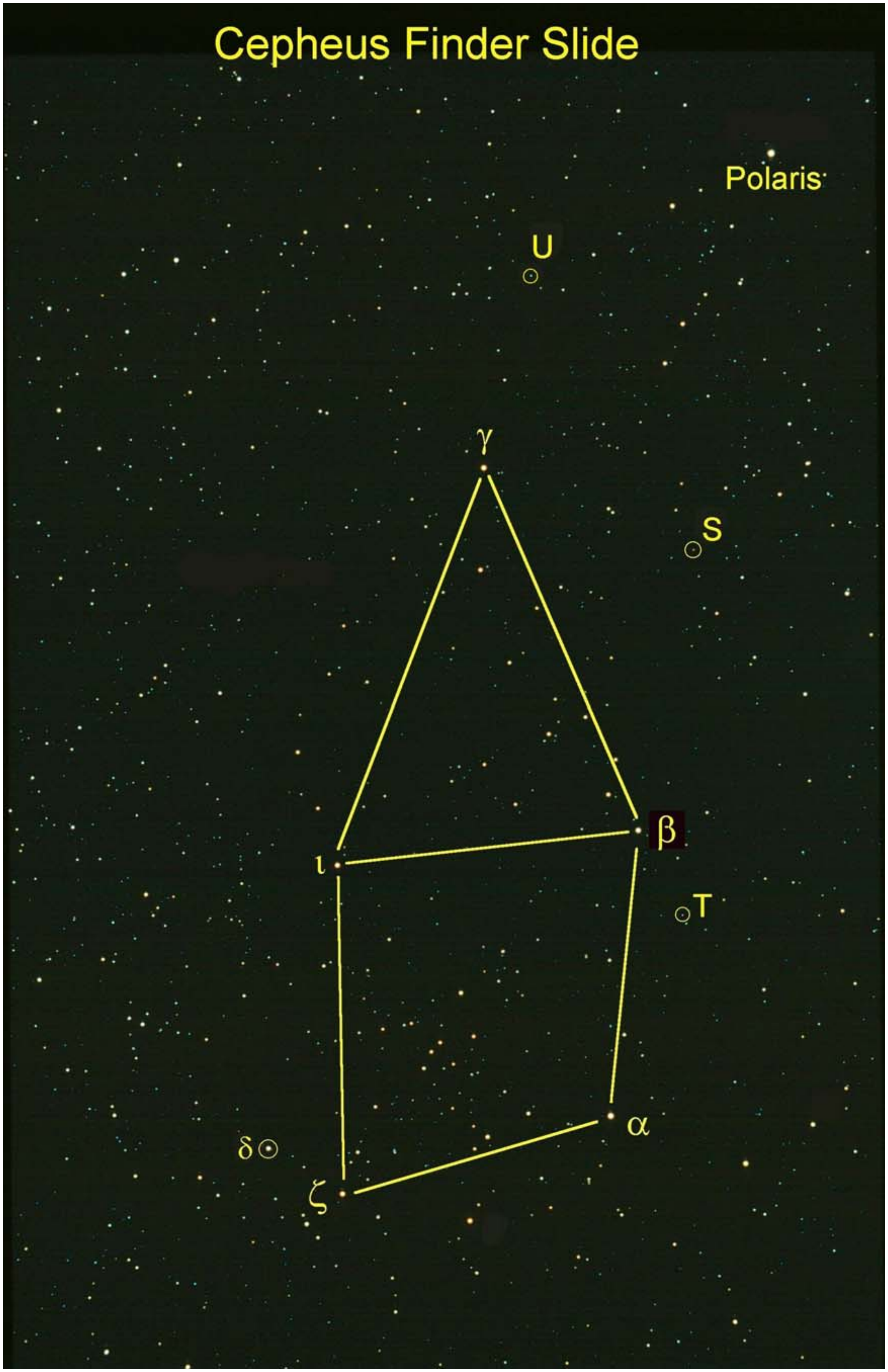

Auriga Finder Slide
R
β
α
θ
RT
ι
β Tauri

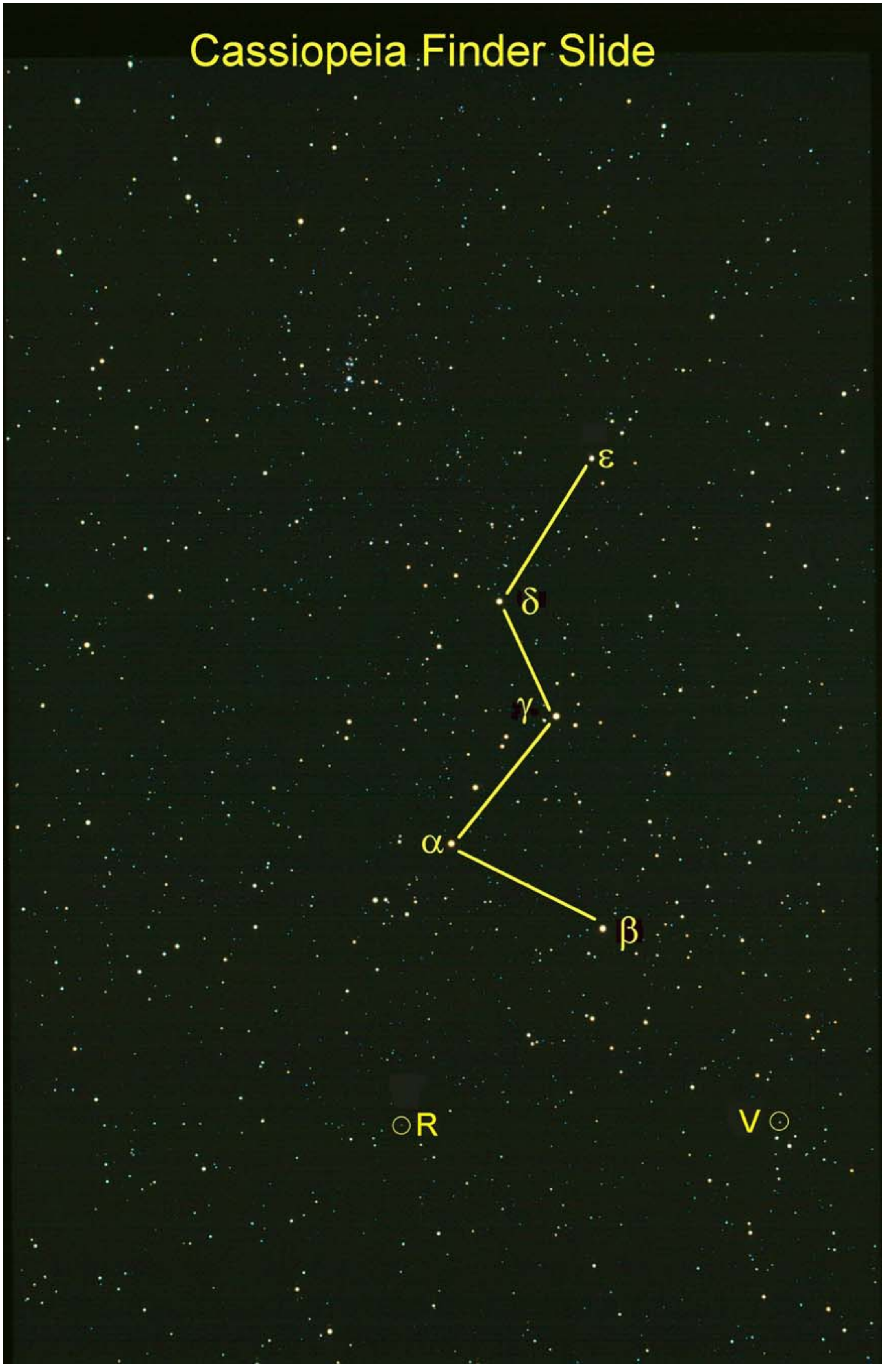

Ursa Major Finder Slide
R
α
β
Z
γ
δ
S
ε
ζ (Alcor & Mizar)
η



Cygnus Finder Slide
W
α (Deneb)
U
γ
X
δ
ε
η
χ
β


W Cygni Finder Slide
W
64
61
53
55
59
67
69

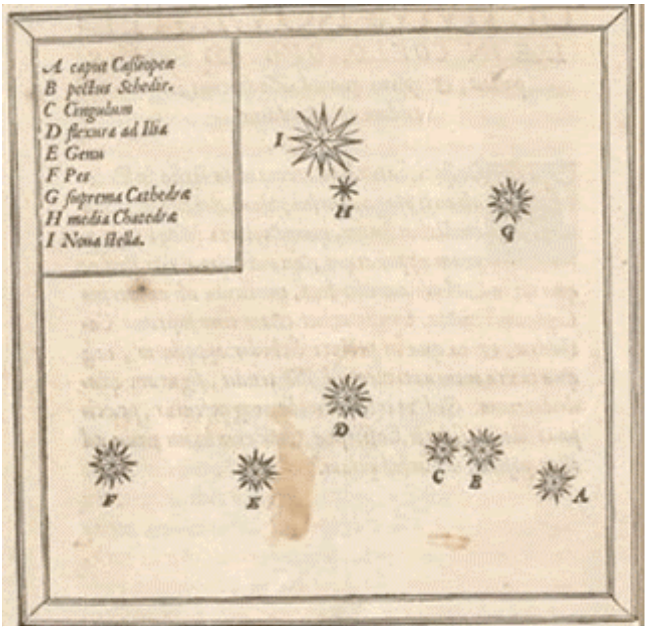

Cepheus Finder Slide
Polaris
U
γ
S
β
ι
T
α
δ
ζ


Cassiopeia Finder Slide
ε
δ
γ
α
β
R
V

Poster Page: Astronomy is for Everybody (the AAVSO)

The AAVSO is not the only organization in the world with a variable star database. Other organizations around the world have databases. Some are specialized, keeping only eclipsing binary observational data, for instance. Do countries exchange information? Do organizations exchange information? How active are variable star observers in Germany? Russia? China? France? England? What types of professional organizations utilize the AAVSO International Database? What do they utilize the information for? In later chapters you will be introduced to HIPPARCOS; what other satellites make use of contributions from amateur variable star observers?

Chapter 6: Measuring Variable Stars Visually



Tycho Brahe's Drawing of the Supernova of 1572

Introduction

Most stars seem to shine with constant light. Thousands of stars, however, are known to change in brightness. Because most changes are not immediately apparent, for centuries the stars were considered to be unchanging. Exceptions were a few instances when Chinese, Arabic, and Native American cultures recorded the sudden appearance of "new" stars—now known to have been novae or supernovae. In 1572 Tycho Brahe discovered a bright supernova in Cassiopeia, and the Western world became acquainted with stars that vary in brightness.

The first astronomer to study variable stars seriously was a German named F. W. A. Argelander (1799–1875), famous for his star atlas and catalog, *Bonner Durchmusterung*. Argelander also recognized that astronomy enthusiasts could help contribute a great deal to the understanding of variable stars. Amateur astronomers around the world observe these exciting stars and assist professional astronomers by sending their data to variable star organizations, such as the American Association of Variable Star Observers (AAVSO) in Cambridge, Massachusetts. You can study the behavior of variable stars by measuring their changes in brightness. You can then draw their light curves, which will allow you to begin to unravel the stories of their turbulent lives.

The collection and study of variable star data requires the ability to estimate magnitudes. If you live in a city, you may be able to see only a dozen stars with your unaided eye in the entire sky. On a moonless night, at a very dark site, you may be able to see several *thousand* individual stars. It can be very difficult to learn to estimate magnitudes if either of the two above situations exist, because either all the stars you need are not visible, or so many stars are visible that the ones you need are lost in the multitude. The variable stars we will be studying are located within the five constellations you became familiar with in Chapters 4 and 5. To further assist you in acquiring the skill of estimation, we will not start with the real sky, but with a set of pictures, sky charts, prints, and slides especially prepared by the AAVSO for this activity.

Investigation 6.1: Interpolation

Your instructor will give you an assorted set of at least ten cylinders. Using a string and a ruler, measure the diameter and circumference of each cylinder and enter the data in the table below.

CYLINDER MEASUREMENTS

#	Circumference (cm)	Diameter (cm)
1.		
2.		
3.		
4.		
5.		
6.		
7.		
8.		
9.		
10.		

These pairs of values can be presented as ordered pairs on a graph. Using the following instructions for graphing to guide you, plot the circumference as a function of the diameter of the cylinder. Another way to say this is "plot the circumference versus the diameter." Still another way to put it is "plot the circumference on the vertical axis (y-axis) and plot the diameter on the horizontal axis (x-axis)." The independent variable is always plotted on the horizontal x-axis while the dependent variable goes on the vertical y-axis.

Graphing Techniques

1. Place a title on the graph paper somewhere near the top of the page. If your graph is going to be wider than it is tall, then the title should still be at the top of the page.

2. Select a scale for each axis so that the graph will cover more than half the page in each direction. Your graph should be centered on the page.

3. On each axis indicate the scale divisions, the name of the variable being plotted (circumference and diameter), and the units of measurement.

4. The *origin* is at the lower left-hand corner of the graph and usually has a value of zero. The numbers increase from left to right along the horizontal (x) axis and from bottom to top on the vertical (y) axis.

   NOTE: Not all graphs follow this rule. Since the larger the positive number for the magnitude of a star the dimmer it is, magnitude numbers plotted on the vertical (y) axis start with larger, positive numbers at the bottom and end with smaller and negative numbers at the top! [Remember, the brighter the magnitude of a star, the smaller the number.]

5. Circle data points to represent graphically uncertainty of data and to ease the drawing in of the “best fit curve” (a straight line is considered a “curve” in this context). We will refer to these circled data points as “error circles.”

6. After all data are entered on the graph, draw a thin line that best represents, as you infer it, the *total* accumulation of data. Follow the *trend* of the data points with a smooth curve. Your line should either go through, or as near as possible to, as many error circles as possible. Start your line at your first data point and end it with the last point. If you continue your line either to the origin or beyond the last point, then make it a dotted line. There may be a measurement that doesn’t seem to fit the trend you see. If so, should you remeasure that data set and try to include it in the trend of the data set, or should you simply ignore it? This is science and there is always error in measurements. Most graphs will NOT be drawn dot-to-dot. When you draw dot-to-dot, you are giving more importance to individual measurements than to the collection of all measurements. In variable star astronomy, it is the accumulation of all the data that is significant, as it is in the measurements of the cylinders.

Now you are ready to answer the following questions by analyzing the results on your graph.

1. What shape is your “best fit” curve? What does this tell you about the relationship between the two variables you plotted, circumference and diameter?

2. Choose a diameter value that you did not measure, that lies along the line you drew but is not a data point on the graph. Reading from the vertical axis, what would be the circumference for this diameter? You have just used *interpolation* to determine an answer. Anytime you can get a number you did not actually measure between two points you did measure, you are interpolating. Determine what the circumference would be for a cylinder with a diameter that is 5 cm larger than your largest measured diameter. For this you need to go along the dotted line outside of your last data point. This is called *extrapolation.*

3. Draw straight lines to both the x-axis and the y-axis from two different points along the line you drew through the data points, choosing two points where no data are plotted. For each axis, subtract the smaller value from the larger one, then divide the value for the y-axis by the value for the x-axis. This will give you the *slope* of the line, or the “rise” over the “run.” Does this number look familiar?

You will further analyze the results from this investigation in Core Activity 6.3.

Core Activity 6.2: Estimating Magnitudes Using Interpolation

To estimate magnitudes of variable stars, you will need to interpolate. Interpolation is the process of estimating a value between two known values. Near the variable star you will be observing are two or more comparison stars of known magnitude. These stars do not change in brightness and are used to compare the brightness of the variable star. Knowing the values of the magnitudes of the comparison stars and the magnitude range of the variable star itself, you can interpolate or estimate the magnitude of the variable star as it changes over time.

1. Given below are three star fields (see Figure 6.1). The magnitudes of the comparison stars are given. Estimate to the nearest tenth the magnitude of the star (offset by the lines in each field [- -]). NOTE: In star fields, the decimals are not indicated. A magnitude of 6.4 is written as 64, so that the fields are not as cluttered and the decimal points are not mistaken for stars.

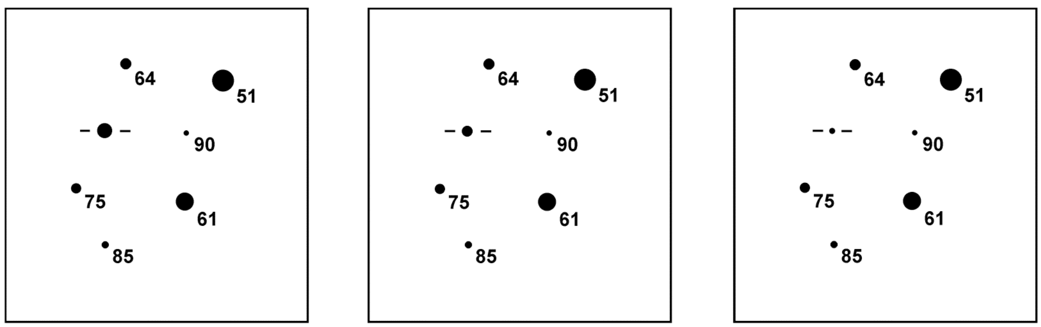


Figure 6.1

In field A, the magnitude of the variable star seems to lie between 6.1 and 6.4, almost half way, maybe a little closer to 6.1, so the magnitude estimate is 6.2. Your estimate may be different from this and that is okay. Write your own estimate in the table below.

estimate of magnitude	star field A	star field B	star field C
yours			
classmate #1			
classmate #2			

Make estimates on the other two star fields. Also record the estimates made by two of your classmates. Do your estimates differ from theirs?

2. Compare your estimated magnitudes with those of the rest of the class. Does everyone have the same answers?

Core Activity 6.3: How Accurate Are Your Results?

MEASUREMENTS AND ERRORS

You learned how to interpolate data in Investigation 6.1 using measurements of diameter and circumference. If you had used a different method of measuring the cylinders, such as trying to use a straight ruler instead of string, your results would have been less accurate. Even with the string, your measurements were not exactly the same as your classmates'. Even though the sizes of the cylinders were the same, the measurements were different. In astronomy, as in other sciences, ***no measured quantity is ever exact***. There is always some error or uncertainty. We can safely use the results from our data analysis only when we can estimate the size of the errors involved. In our everyday lives, the terms *precision* and *accuracy* are used interchangeably, but in science there is an important difference. Precision pertains to the process of making a measurement, while accuracy pertains to the results of the measurement.

Precision of the measuring instrument is a way of describing how close the measurements in a data set are to each other, given that the measurements have been made in the same way. When a 1 kg mass is weighed three times on an imprecise instrument, for example, the measurements may range from 0.8 kg to 1.2 kg. When it is measured on a more precise instrument, however, the measurements will vary less and have a smaller range.

The precision of each measurement is improved as each individual measurement is more sharply defined. When we are trying to make a precise measurement, we should always measure to the limits of the instrument by estimating tenths of the smallest division. If a ruler has only centimeters marked on it, for example, we should still estimate to the nearest millimeter when making a measurement. The number of decimal places (not the number of digits) in the measurement indicates the precision of an individual measurement.

Accuracy is a way of describing how closely a measurement agrees with the true or accepted value of the quantity being measured.

The difference between an observed value and the true or accepted value is called the *absolute error* or *percentage error*. The larger the absolute error, the poorer the accuracy. Percentage error is a useful indication of accuracy; however, an error of 1 meter can either be large or insignificant, depending on whether you are measuring the distance to a star or the distance to the front of this room. The percentage error is given by:

$$\%\ \text{Error} = \frac{|\,\text{Measured} - \text{Accepted Value}\,|}{\text{Accepted Value}} \times 100$$

For example, your measurement for the diameter of a coin is 24 mm, and the accepted or actual diameter is 25 mm. Then the percentage of error is:

$$\%\ \text{Error} = \frac{|\,24 - 25\,|}{25} \times 100 = \frac{1}{25} \times 100 = 4.0\%$$

Exercise

1. Using your results in Investigation 6.1, calculate your percentage error for the slope of the best fit line. The accepted value of p is 3.1416; do you think your individual percentage error is larger or smaller than the class average?

2. Compare your calculated percentage error with the calculated error for the entire class. Discuss the precision of your measurements, the accuracy of your results, the percentage error, and any errors or other factors that might have influenced the results.

3. Measure the diameter of a quarter and a nickel with a ruler calibrated in millimeters. Think about how many decimal places there should be in each reading and why.

   Diameter of the quarter = _______ Diameter of the nickel = _______
   Which digit is the estimated digit?

SIGNIFICANT DIGITS

Another indicator of the accuracy of a measurement is the number of significant digits. Significant digits are digits with a numerical value we are reasonably sure of (since every number contains some range of uncertainty). If we see the measurement 1.1, for instance, we know by convention that the true value is somewhere between 1.05 and 1.15. But how do we know how many significant digits we should give it in the first place? The rules are as follows:

1. All non-zero digits are significant, so 1239.54 would have six significant digits.

2. Zeros surrounded by nonzero digits are always significant, so 1045 has 4 significant figures.

3. A final zero or trailing zeros are significant only when not holding the decimal place (i.e. when a decimal point is present), so 10400 has 3 significant figures, 0.004500 has 4, 163.00 has 5 and 100. has 3 significant figures.

4. If we arrive at a number through counting, then the number is considered exact and is said to contain an infinite number of significant digits. If we count ten fingers on our hands, for example, there are exactly 10 fingers, not 11 or 10.2 fingers. We can consider the number to be 10.00000...all the way to infinity.

5. Numbers obtained through definitions or defined quantities also contain an infinite number of significant digits. For example, the symbol pi (π = 3.141592654...) represents an infinitely accurate number.

Exercise:

a. 0.147 mg _____

b. 235 kg _____

c. 0.0033 cm _____

d. 0.3005 ly _____

e. 5001 parsecs _____

f. 0.03 mag _____

g. 670,000 km _____

h. 50.5 ly _____

i. 7.8235 meters _____

j. 0.02040 s _____

6. When you are doing calculations with given numbers and are not told how each number was calculated, you should keep the “Weakest Link Rule” in mind (that is, “A chain is only as strong as its weakest link,” in this case meaning that a calculated answer cannot be more accurate than the most inaccurate number used). If a series of calculations involves one very imprecise number, no matter how accurate the other numbers are, the final answer cannot be more accurate than that one imprecise number.

   For addition and subtraction, the final answer should have the same number of decimal places as the least precise number.

   45 + 10.31 – 6.009 = 49 (45 is the least precise number with 0 decimals)

   45 + 10.81 – 6.009 = 50. (round up and then drop the insignificant digits, use a decimal point after the zero to show the zero is significant)

   For multiplication and division, the final answer has as many digits as the least accurate number (fewest significant digits). Thus:

   6 x 0.003 = 0.02 (not 0.018 — because 0.003 has one significant digit and so the answer can only have one significant digit. 0.018 has two significant digits, 0.02 has only one.)

   Evaluate the following:

   a. 78.52 – 6.4 = __________

   b. 1.89 + 3.9 = __________

   c. 32.02 x 5.68 = __________

   d. 23.99 x 3.28 = __________

The “rules” above are the accepted scientific method of determining the accuracy of a measurement, and should be followed whenever possible. You should never simply round off your answer to two decimal places, because the precision of the instrument you used to make the measurement is never the same. As you know by now, there are many inaccuracies in scientific measurement which we must take into account. Science is not like math, where every number is infinitely accurate, because in science all kinds of systematic and random errors can happen.

SYSTEMATIC VERSUS RANDOM ERROR

In variable star observation there is both *systematic error* and *random error*. Systematic errors are those that never cancel out and are relatively constant. They can occur when the variable star observer is biased in his or her observations. It is scientifically improper to force any “improvements” of an observation to fit what you believe is a pattern. Never manipulate the data. Don’t worry if the result is not exactly what you expected, just record what you see. The effect of random errors (sometimes referred to incorrectly as “human” error), on the other hand, tends to diminish over time. In fact, random error decreases in proportion to the square root of the number of measurements, so even a few additional measurements will increase the accuracy of the entire set. The average of four measurements, for example, will have only half the error of one measurement. Were the errors that occurred in measuring the circumferences and diameter of the cylinders random or systematic?

The Names of Variable Stars

You have become familiar with the convention of naming stars in a constellation with letters from the Greek alphabet, ranked from brightest to dimmest, followed by the possessive Latin form of the name of the constellation, for example: alpha Orionis (Rigel). Variable stars, however, have a different identification system. Variable stars are often not bright stars within a constellation, and since they can have a large range of variation, naming them as part of the brightest to dimmest system results in confusion. There are also more stars within most constellations than there are letters in the Greek alphabet.

Variable star names are assigned in the order in which the variable stars were discovered in a constellation. If one of the stars that has a Greek letter name is found to be variable, the star will still be referred to by that name. Otherwise, the first variable in a constellation would be given the letter R, the next S, and so on to the letter Z. The next star is named RR, then RS, and so on to RZ; SS to SZ, and so on to ZZ. Then the naming starts over at the beginning of the alphabet: AA, AB, and continuing on to QZ. This system (the letter J is always omitted) can accommodate 334 names. There are so many variables in some constellations in the Milky Way, however, that an additional nomenclature is necessary. After QZ, variables are named V335, V336, and so on. The letters representing stars are then combined with the possessive Latin form of the constellation name the same way that the Greek alphabet is used for complete identification of the variable star. Examples are SS Cygni (SS Cyg), AZ Ursae Majoris (AZ UMa), and V338 Cephei (V338 Cep).

Friedrich Argelander initiated this system of nomenclature. He started with a capitalized R for two reasons: the lowercase letters and the first part of the alphabet in capital letters had already been allocated for other designations, leaving capitals towards the lower end of the alphabet mostly unused. Argelander also believed that stellar variability was a rare phenomenon and that no more than 9 variables would be discovered in any constellation (which is certainly not the case). Why the J is always omitted is a mystery lost in the dusty annals of astronomical history.

The AAVSO also uses a second system of names—a numerical designation. This numerical designation, called the Harvard Designation (after Harvard College Observatory, where the system was first used), is a group of six numbers and a sign that give the variable's approximate coordinates for the year 1900. The first four digits give the hour and minutes of right ascension; the last two (with a plus or minus sign) the degrees of declination. For example, the designation 0942+11 for R Leonis denotes an approximate position of right ascension of 09 hours 42 minutes and a declination of $+11^{\circ}$ for the year 1900. What is the advantage of using the Harvard Designations?

The Dangers of Radiation

The largest source of natural radiation comes from the radioactive decay of unstable elements within the Earth's crust, such as uranium-238, potassium-40, and radon-226. As a result, we are constantly exposed to radiation from granite and other rocks, soil, hot springs, and building materials. We also ingest foods which contain radioactive isotopes such as potassium-40, originally part of fertilizers which leached into the soil and crops. We are exposed to radiation from cosmic rays, charged atomic particles moving at almost the speed of light which enter our atmosphere. In the upper atmosphere almost 90% of all cosmic rays are fast-moving protons. The higher the elevation, the greater the exposure to high-level radiation from cosmic rays. The majority of these cosmic rays do not reach the surface because of the Earth's magnetic field, which produces the donut-shaped Van Allen belts that trap the fast-moving protons. Most of the charged particles in the Van Allen Radiation Belts originated in the solar wind that streams out from the Sun's corona. In the polar regions radiation leaks out of the Van Allen Belts and ionizes the air, producing brilliant displays called aurorae.

Space Walk

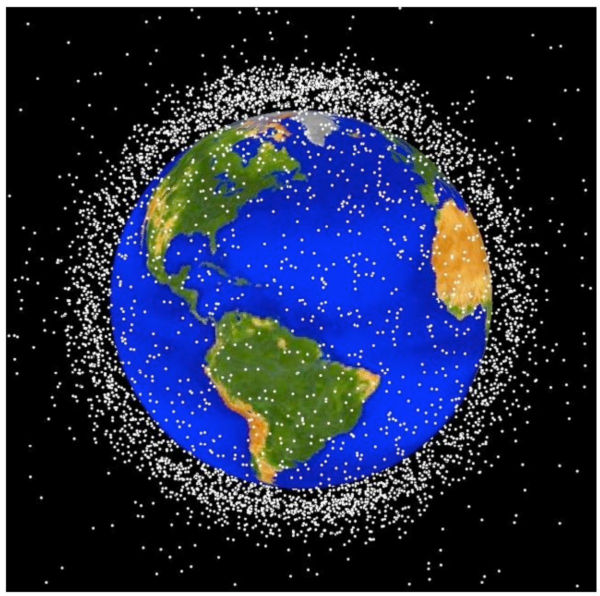
The Earth's magnetic field is offset from its center. Besides being inclined at about 11^{o} to the rotational axis, the magnetic axis passes through the equatorial plane at about 500 kilometers toward the western Pacific. This means that on the opposite side of the globe, above the western Atlantic at around 30^{o} south latitude, the inner radiation belt extends down into Earth's upper atmosphere to an altitude of only about 200 km. Centered off the Brazilian coast, this region of the sky is known as the South Atlantic Anomaly (SAA). In this area satellites can suddenly and mysteriously start malfunctioning, cutting power to vital subsystems, spinning dangerously out of control, and even closing down all systems. The radiation environment produces an electronic nightmare for satellites in this area at altitudes below 1000 km. The Hubble Space Telescope (HST) occupies a circular orbit about 600 km high and has a low 28.5^{o} inclination, which means HST passes through the SAA on 9 or 10 successive orbits daily, with encounters lasting as long as half an hour.

Satellite exteriors, internal structures, and electronics packaging provide sufficient protection against electrons, but higher-energy protons can still get through. Sensitive devices are placed in more protected areas of the satellite, and provided with extra radiation shielding if possible. Sometimes instruments must be turned off for the duration of SAA passages. Some spacecraft components cannot be protected, such as solar-cell arrays, which suffer from constant and continuous degradation due to radiation.

If instruments and electronics must have extra protection against the radiation in the SAA, what about astronauts and scientists who encounter this area for extended periods of time? When the space station Freedom is constructed, the astronauts and scientists aboard will have to be prepared to deal with this potentially hazardous radiation exposure. NASA is studying the radiation dangers posed by working and living in space. Several space shuttle missions have carried a model of a human skull covered with synthetic skin and filled with sensors to detect radiation. NASA is using the data to redesign space suits and helmets to incorporate greater radiation protection for future space-dwellers. Exactly what dosage of radiation is acceptable is difficult to determine.

The effects of ionizing radiation on living organisms are divided into two categories: genetic damage and somatic damage. Genetic damage occurs when the DNA molecules in the genes of a person's reproductive organs are altered, causing a mutation. These genetic changes are passed on to future generations. Somatic damage involves cellular changes caused by ionizing radiation in all other parts of the body except the reproductive organs. Of major concern is the induction of various forms of cancer. It is difficult to assess the risk of cancer or other forms of damage as a result of exposure to even low-level ionizing, or natural, radiation. Populations in regions where the background radiation is higher than normal show no apparent effect of their exposure. Yet it is nearly impossible to make an accurate comparison with other populations because of differences in diet, social habits, and ethnic origin.

Radiation is not the only orbital danger for spacecraft. Space exploration has produced increasing amounts of space debris, which is becoming a problem. Space debris, also referred to as "space waste," is defined as any useless object in space, regardless of size. It covers objects of all sizes, from large inactive satellites or burnt-out rockets, to freely flying nuts and bolts, down to objects of a fraction of a millimeter, such as flakes of paint. Orbital debris refers to debris in orbit, while re-entering debris means space debris re-entering the dense layers of the atmosphere or impacting on the ground or on the surface of the ocean. Trackable debris means debris which is large enough to be detected and tracked by present radar and telescopes and which can be attributed to a specific launch. Non-trackable debris is debris too small or too infrequently observed to enter the category of trackable. The size of trackable debris is approximately 10 cm in low orbits and 1 m in geostationary orbit.



Computer generated image of space debris in a low Earth orbit - NASA Orbital Debris Program Office

The number of trackable objects orbiting the Earth at the end of June, 1991, was reported to be 7025 by the US Space Command. This does not include any objects smaller than 10 cm in diameter. According to US estimates, the amount of debris, including untrackable objects of more than 1 mm in diameter, is 3,500,000 pieces. The total mass of these objects is estimated to be 3000 tons. The debris in low Earth orbit (LEO) is the most serious threat, because most satellites, including HST, the Space Shuttle, and the future space station Freedom occupy LEO. The orbital velocity of objects in LEO is about 7km/s. The relative speed of debris at encounter depends on the angle of orbit crossing. The average is 10 km/s. The high kinetic energy of these objects results in severe damage when collisions occur. An aluminum sphere of 1 cm in diameter has the equivalent energy of a mid-size car moving at 50 km/h. There were 104 cases of breakup recorded by the end of June 1991. These breakups are believed to have created many untrackable pieces of small debris, and most breakups took place in LEO. Freedom will have to be able to withstand collisions with objects of up to a few centimeters in diameter, the equivalent of being run into with a Mack truck.

Are nations responsible for space debris? Is it a legal issue? A moral issue? It is impossible to account for ownership of space debris and the damage it inflicts, especially for untrackable debris. What should be done? Should periodic sweeps try and clean up at least the trackable debris before it deteriorates into untrackable debris? Should nations contribute to funding for this problem equally? According to the percentage of orbital launches? Should we be concerned with space litter the same way we are concerned with highway litter here on Earth?

Core Activity 6.4: More Magnitude Estimations

1. Look at the slide projected on the screen. You will recognize it as Cassiopeia, one of the five constellations in the HOA program. Draw the pattern of six stars that make up the distinctive "W" of the constellation in the space provided below.

2. Alpha Cas has an apparent magnitude of +2.2, while the dimmest star in the pattern, epsilon Cas, has a magnitude of +3.4. Mark these numbers on your diagram and estimate the magnitudes of each of the remaining stars in the "W" based on the brightness of alpha and epsilon. Place your estimates on your constellation diagram.

3. Your instructor will give you the actual magnitudes of the stars in the pattern to a tenth of a magnitude. Calculate the percentage error for each of your estimates using the following table.

Table 6.1: Measurement Errors in Magnitude Estimations

Star Designation	**Difference Actual - Your Estimation**	**% Error**
beta Cas		
*gamma Cas		
delta Cas		

*variable star

4. Place your values for the three magnitudes into a class table on the board as directed by your instructor. Average them, place your answers in Table 6.2, and calculate the percentage error for your class averages.

Table 6.2: Measurement Errors in Class Data Measurement

Star Designation	Difference Actual – Class Average	% Error
beta Cas		
*gamma Cas		
delta Cas		

*variable star

5. Did the percentage error increase or decrease in the class averages compared to your individual measurements? Discuss why this occurred.

6. How could the percentage error be made even smaller?

7. List at least four sources of error. Are they random or systematic? Why?

Repeat this activity with another constellation. Your instructor will provide another slide with magnitude values for the brightest and dimmest stars.

Constellation drawing:

Table 6.3: Individual Magnitude Estimates and Errors for ________________

Star Designation	Difference Actual - Your Estimation	% Error

Table 6.4: Class Magnitude Averages and Errors

Star Designation	Difference Actual – Class Average	% Error

Julian Day

You will note in Table 6.5 that you are required to record time using the Julian Day. This is the standard unit of time used by astronomers. Time is one of the most important quantities in any physical system. Astronomers often collect data over months or even years, and sometimes analyze very old data (even data taken by ancient observers thousands of years ago). It is essential that we use an efficient and unambiguous method for recording time.

The usual system of calendar dates has changed several times in the past and is not accurate enough for astronomical use. The Julian calendar was devised on orders from Julius Caesar. Prior to this, at different periods of time there were different numbers of days in a year. The dates kept getting out of synchronization with the seasons, and to "catch up," Caesar ordered that 45 BC contain an extra 90 days. He also added the leap year to keep the dates from changing seasons.

The modern Gregorian calendar was introduced by order of Pope Gregory XIII in late 1582. The reason for the new calendar was that by 1582, the Julian calendar was 10 days out of phase with the date on which Easter had occurred 1250 years earlier. In order to "catch up," Pope Gregory XIII dropped 10 days from 1582: Thursday, October 4th of the Julian calendar was followed by Friday, October 15th of the Gregorian calendar. Most countries adopted the Gregorian calendar as soon as it was put forth; however, Great Britain and its American colonies did not adopt it until1752. At this time 11 days had to be dropped from English and American calendars to have the same date as the rest of the world. Also, the beginning of the year was changed from March to January. George Washington's birthday was February 11, 1731; however, with the changes in 1752, Washington's birthday became February 22, 1732. As you can see, ancient dates are unreliable.

Astronomers simplify their timekeeping by merely counting the days. Each date has a Julian Day number (JD), which is simply the number of elapsed days since January 1st, 4713 B.C. For instance, January 1st, 1993, was JD 2448989; January 2nd, 1993, was JD 2448990; and January 1st, 2000, will be JD 2451545. (NOTE: The Julian Day is NOT the Julian calendar) Why the year 4713? The Julian Day system of numbers is a continuous count of days elapsed since the beginning of the Julian Period. This period was devised by Joseph Justus Scaliger, a French classical scholar in the 16th century. Scaliger calculated the Julian Period by multiplying three important chronological cycles: the 28-year solar cycle, the 19-year lunar cycle, and the 15-year cycle of tax assessment called the Roman Indiction.

The solar cycle is the shortest period in which the same days of the week return to the same days of the year in the Julian calendar. For example, if October 25th fell on a Monday one year it would require 28 years for October 25th to fall on a Monday once again. The 19-year lunar cycle is also called the Metonic cycle. It is named after Meton, a Greek astronomer in the 5th century B.C., who discovered that 235 lunations (phase cycles) occur in 19 solar years. In other words, if a full Moon occurs on September 18th, it will take 19 years for a full Moon to fall once again on September 18th. Both of these cycles started a new cycle close to 1 B.C.: the solar cycle in 9 B.C., and the lunar cycle in 1 B.C. The Roman Indiction started in 3 B.C. Therefore, 1 B.C. marked the 9th year of the solar cycle, the 1st year of the lunar cycle, and the 3rd year of the Roman Indiction. To establish a beginning point for his Julian Day system, Scaliger calculated the closest date before 1 B.C. which marked the first day for the beginning of all three cycles. This day is January 1, 4713 B.C., which is Julian Day number 1.

Core Activity 6.5: Collecting Your Own Data

To access html, flash, and powerpoint versions of this activity go to *Activity #1: Stellar Heartbeats* at http://chandra.harvard.edu/edu/formal/variable_stars/

1. The next few pages show a series of reproductions of a star field, simulated to show the variability of a star (indicated by an arrow).
2. Estimate the magnitude of your variable star on the first picture of the star field using the magnitudes of the stars around it. Notice that the comparison star magnitudes are given without decimal points, so 38 is actually 3.8 and105 is 10.5. This convention was adopted so that decimal points would not be mistaken as field stars and to eliminate unnecessary clutter.
3. If you now feel comfortable estimating magnitudes, proceed through each of the pictures and place your data in Table 6.5 and on the board to complete Table 6.6.

Table 6.5: Data for Variable Star X

Julian Day	Magnitude		Julian Day	Magnitude

Table 6.6a Class Magnitude Estimates of Star: Magnitude Estimates of Students

Student ID →																				
Julian Day ↓	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
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Table 6.6b Class Magnitude Estimates of Star: Magnitude Estimates of Students

Student ID →																				
Julian Day ↓	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**
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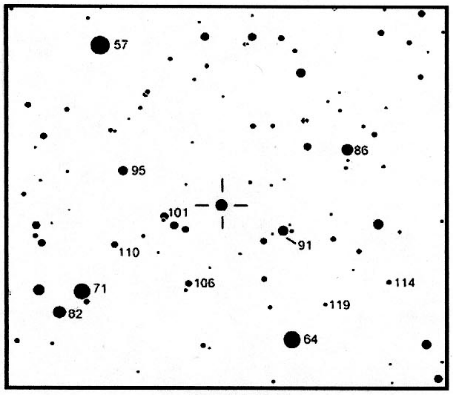
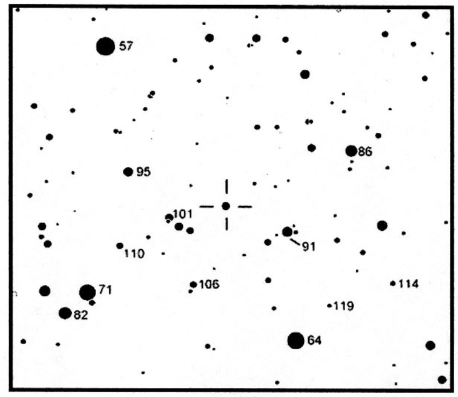
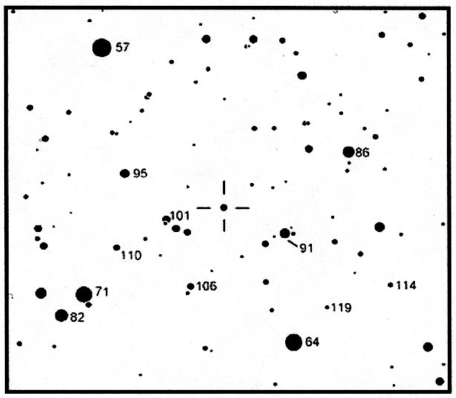


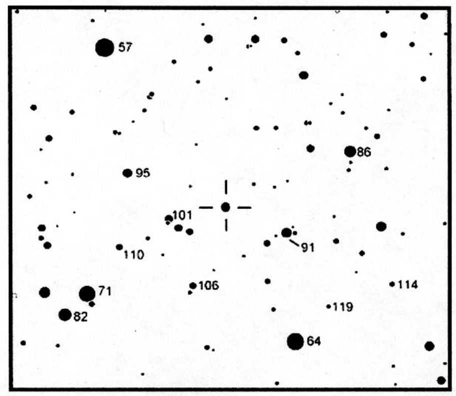
JD 2449050



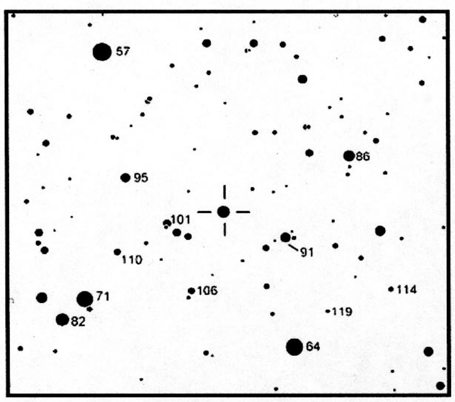
JD 2449110



JD 2449150



JD 2449180



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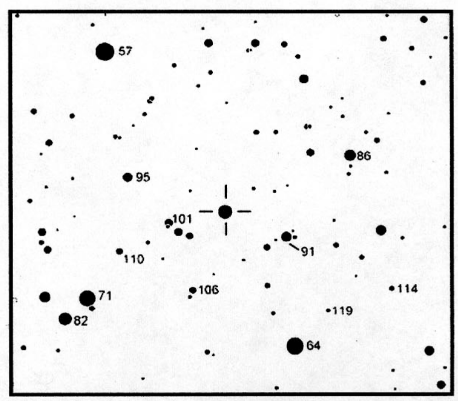
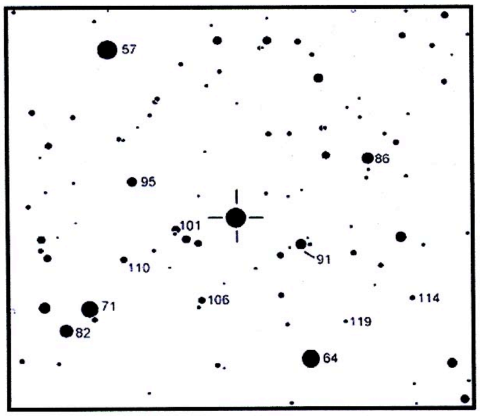
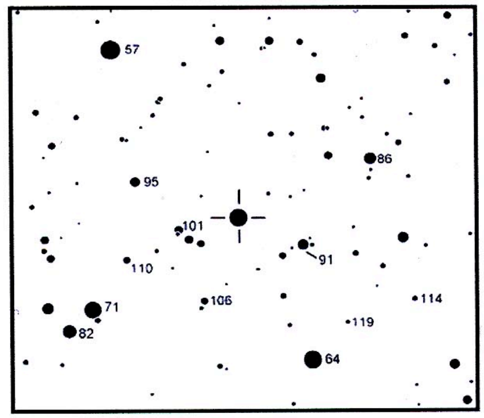


JD 2449300

4



JD 2449350



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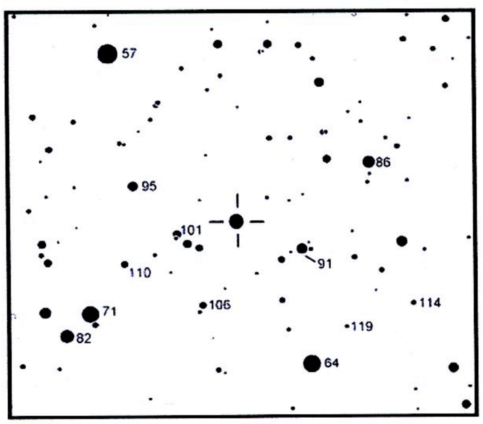

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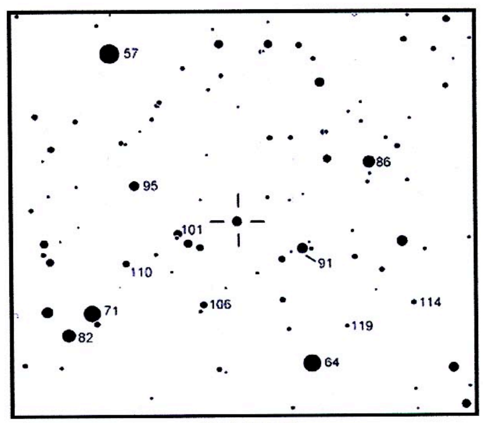

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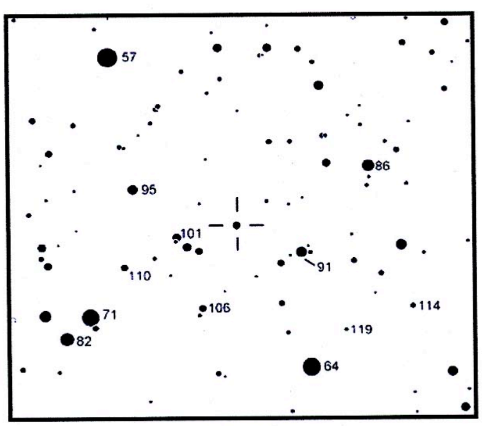
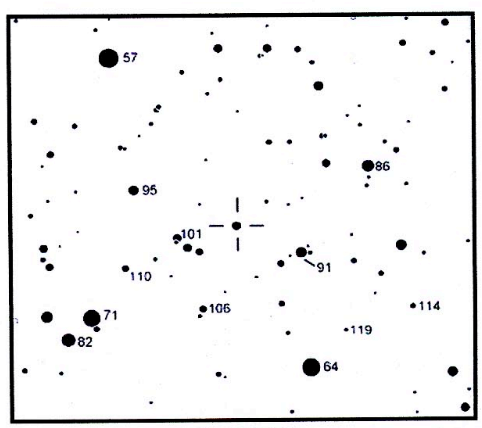
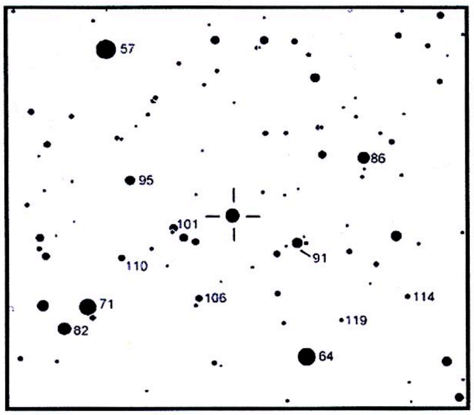


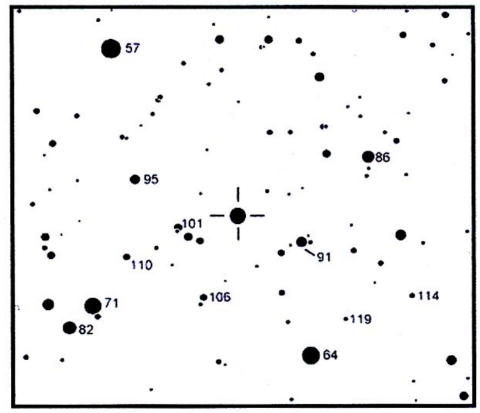
JD 2449540



JD 2449635



JD 2449700



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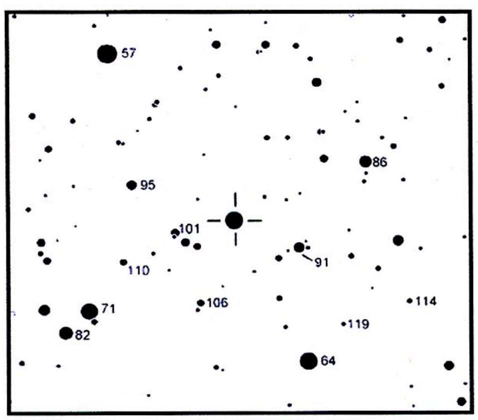
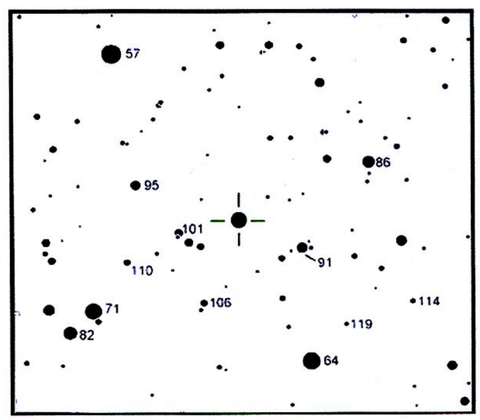
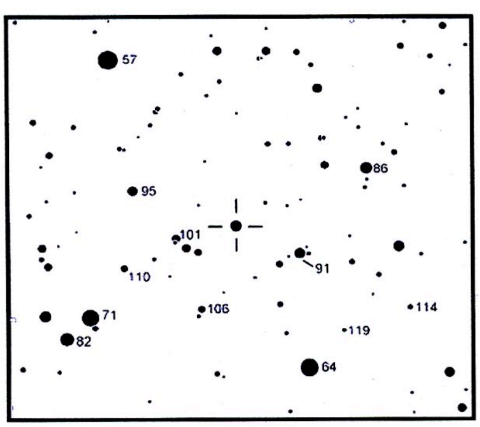


JD 2449760



JD 2449800



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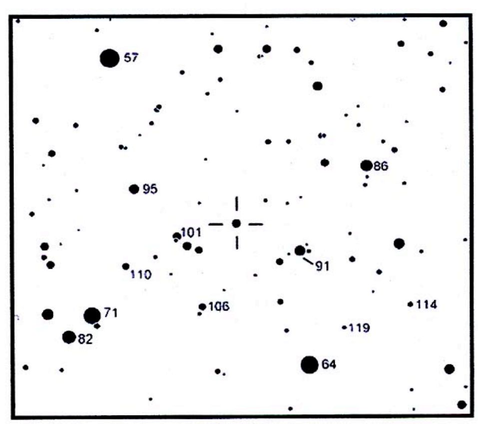


JD 2449950

Who Are the Amateur Astronomers?

In 1997, Mary Dombrowski, when a sophomore at Glastonbury High School, Glastonbury, CT, was the youngest person to submit a research project to the National Young Astronomer Award competition. Her project was a study of IP Pegasi, a cataclysmic variable star which ranges from about 12th to 17th magnitude. This star is very difficult to observe visually when it is faint, but can be easily observed during its outbursts. Mary regularly observed this star, plotted light curves of her observations, and then analyzed them. Mary showed how an analysis of the light curve helped to explain the presence of a companion star which eclipses IP Peg, and the eclipse can be observed during outbursts. For her work, Mary won 4th place in the National Young Astronomer competition.

In 1998, Mary won the First Place Award at the Connecticut Junior Science and Humanities Symposium for her research paper entitled "Cataclysmic Stellar Variability with Eclipsing Binary Superimposition." This award entitled her to a $4,000 scholarship to a college of her choice, or a $10,000 scholarship to attend the University of Connecticut.

Mary's research projects did not just happen, they grew out of her involvement and development as an amateur astronomer. She became interested in observing variable stars from her father, an experienced amateur astronomer, and learned from him how to make regular monthly observations, and submit them to the American Association of Variable Star Observers (AAVSO). After learning the basics, and gaining some experience, Mary soon became an expert variable star observer. And once she became good at making observations, she began to think more about the stars she was observing. She learned about the various types of variable stars, how they behaved, and especially about how a star's light curve can reveal clues about why the star behaves the way it does.

Without the nightly observations of amateur astronomers like Mary Dombrowski, the professional astronomer would find it difficult, if not impossible, to collect the quantity of data that is needed to further the study of stars, the Sun, novae and supernovae, comets and meteors.

Many amateur astronomers at first are astonished to learn that their stargazing efforts can make a real contribution to the advancement of the science of astronomy. There are many organizations like the AAVSO which welcome the participation of amateur astronomers of all ages and from all walks of life. Some groups may have their own area of specialization, but most will encourage an interest in any area of astronomy. These organizations are primarily made up of amateur astronomers: people who all have an interest in astronomy, who might start out with no special knowledge of the subject, but who are driven to learn as much as they can about the areas that interest them.

Why did I choose to study variable stars?

Astronomy has always been a great interest in my life. I am fascinated by the simplest astronomical objects such as the Moon and the Big Dipper. Recently, I have become more involved in astronomy and I have been observing Saturn with its rings nearly edge-on, Jupiter and the impacts made by Comet Shoemaker-Levy 9, a partial solar annular eclipse, and on occasion, the Aurora Borealis. All these objects, even though they are truly magnificent, did not really provide me with the chance to contribute data. I was always an observer but never a contributor to the astronomical community.

Through my research of variable stars I am able to make my own magnitude estimates and contribute them to the AAVSO for possible dissemination to the astronomical community for research purposes. Since I have started my research on variable stars, I have been able to provide useful information for professional scientific studies. I am proud that my observations are helping science. I also have found a lifelong hobby that will enhance my knowledge of astronomy for years to come.

-Mary Dombrowski

You may be surprised to know that some of the most important names in the history of astronomy are those of amateur astronomers. One of the first such names is Tycho Brahe, who became almost obsessed with determining the accurate positions of stars after he discovered a new star in 1572 that was, for a time, brighter than Venus and visible in broad daylight. He reasoned that there may be more such stars and other strange objects appearing, and that the best way to detect them is to have an accurate catalogue and chart of the heavens.

Another widely recognized name in astronomy is that of William Herschel. Herschel was a musician who took up astronomy as a hobby. He learned how to make telescopes and how to make observations. His astronomy work was so good and so valuable that his country, England, awarded him a regular stipend to allow him to do astronomy on a full-time basis.

There are others in the past who started out as amateurs, but whose contributions were so significant they went on to professional careers in astronomy. E. E. Barnard, in the photo at left, discovered a star with the highest known proper motion, now known as Barnard's Star; young English amateur John Goodricke discovered the period of the eclipsing "Demon Star," Algol; Edward Pigott discovered the variability of delta Cephei.

One of the most prolific amateur observers in the 20th century was Leslie Peltier. Leslie grew up on a farm in Ohio. He bought his first telescope with the money he earned picking strawberries for his father. Leslie was an amateur astronomer for life, while he earned his living by working as a farmer, mechanic, toy maker, and stock clerk. From 1918 until his death in 1980 he made over 132,000 variable star observations.

MaryJane Taylor was five years old when she helped her dad build a telescope. She enjoyed it so much that she built her own 6-inch reflector a year later. She then began making solar and variable star observations. As a high school student she spent two summers as a research assistant at the Maria Mitchell Observatory in Nantucket, Massachusetts. In college MaryJane took courses in physics, astronomy, and math. As a graduate student, she was a member of the South Pole Optical telescope team which established the first automated optical telescope at the South Pole. After earning her Ph.D. in astronomy, she worked on a number of important projects, including the Hubble Space Telescope High Speed Photometer. She now is a professor at Loras College, Iowa, where she teaches physics and astronomy, and continues to be active in astronomical research work.

Core Activity 6.6: Magnitude Estimation and Graphing with Slides (and/or prints)

To access html, flash, and powerpoint versions of this activity go to *Activity #2: A Variable Star in Cygnus* at http://chandra.harvard.edu/edu/formal/variable_stars/.

1. View a slide of the constellation Cygnus. Look for the asterism referred to asthe Northern Cross and sketch the pattern of the brightest stars. Rank and label the bright stars on your sketch.

2. Compare the Cygnus finder chart to the slide and your drawing. Note the orientation of the slide and chart. Locate the bright stars on your finder chart and note their names. Locate the variable stars on the finder chart and locate the approximate regions of some of these variables on the slide. A set of prints of Cygnus is also included. You may decide to locate the variables on the first print and mark them on an overhead transparency. You can then move the transparency from print to print to see the changes in the variable stars. NOTE: The positions of the stars may change slightly from print to print.

3. The next set of slides are all enlargements of one-quarter of the Cygnus area and contain the variable star W Cyg. Locate W Cyg on finder chart (aa). The second slide is approximately the same scale as the finder chart (aa). Locate W Cyg. Familiarize yourself with the pattern of stars around W Cyg so that you can locate it easily when it is time to move on to the next slide.

4. Locate the comparison stars for W Cyg on the finder chart, and then identify the comparison stars on the slide. Using the known magnitudes of the comparison stars which are listed on the finder chart, estimate the magnitude of W Cyg from the slide. Repeat for all slides in the set.

5. Plot your magnitude estimates individually and as a group. Sketch a "best fit" curve (called a light curve) through the plotted points and determine the times of maximum and minimum brightness. Make a rough estimate of the period. Compare your results to the actual light curve provided by your instructor.

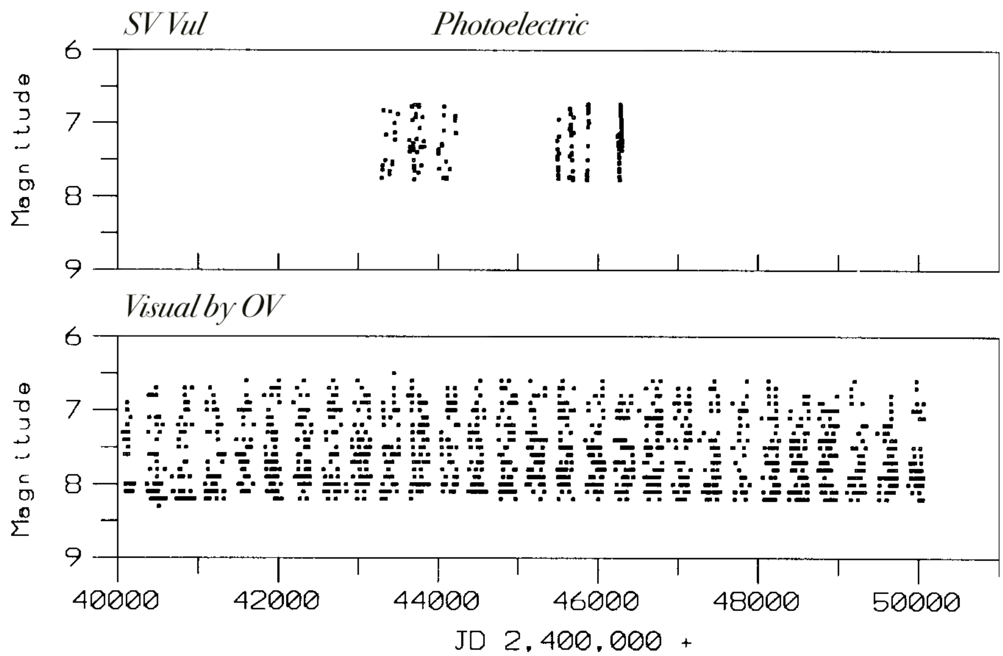
SPACE TALK

Photometry is the measurement of the brightness of a source of radiation over time. The brightness of infrared, optical, and near-ultraviolet wavelengths is measured in terms of apparent magnitude. The human eye can make comparisons accurate to 0.1 magnitude between an unknown star and **comparison stars** of known brightness. *Photoelectric photometry* consists of the measurement of the brightness of a source using electronic devices such as photoconductive or photovoltaic detectors (*photometers*), which convert radiation into an electrical signal whose magnitude can be determined very precisely (to 0.003). Galactic Cepheid variables have been studied both visually and photoelectrically for decades. If photoelectric data have a high degree of **precision**, and visual data have a lower precision, then is it useful or informative to have amateur astronomers study Cepheid variables visually?

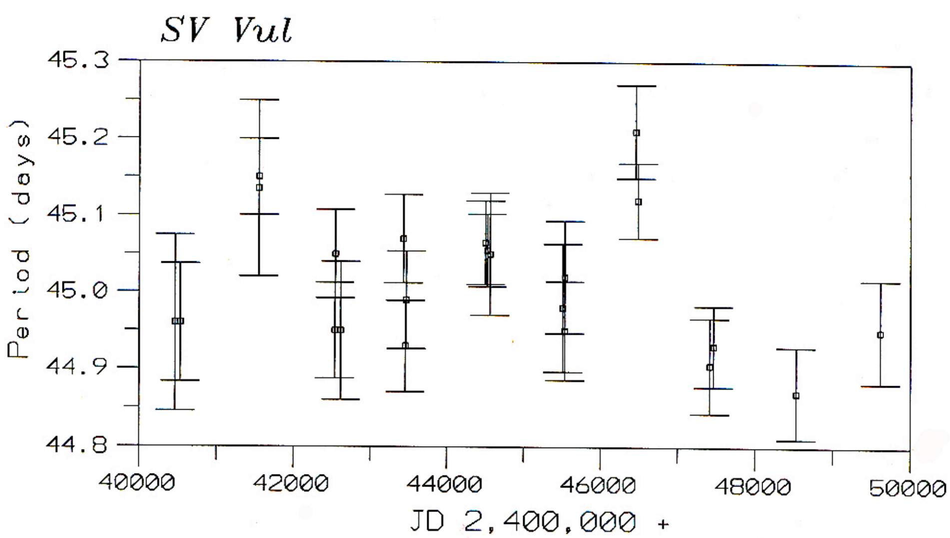
Grant Foster, a mathematician who works for the AAVSO, has provided an answer to this question in a technical paper entitled *"Comparison of Visual and Photoelectric Photometry for Bright Cepheids."* The paper presents the analysis both of available photoelectric data and of visual data from the AAVSO International Database for two bright Cepheid variables, X Cyg in Cygnus and SV Vul in Vulpecula. The visual data selected were contributed by two prolific observers (OV and LX) who have been contributing observations to the AAVSO database for decades.

Cepheid variables have a very low **amplitude**, or difference between maximum and minimum magnitude. Since the **range** in magnitude is small, many researchers believe that these variables are unsuitable for visual study. However, photoelectric observations are sparse, usually consisting of a few days or weeks of monitoring with months or years of unobserved time in between. It is difficult to analyze such sporadic observational records. Any changes between periods of observation may go undetected, and temporary changes may be missed entirely. A well-studied Cepheid may have ~200 photometric observations. Visual observations provide a vast quantity of data, and even more important, the coverage is continuous over long periods of time. Large quantities of data over a very long time span are necessary for any detailed study of the behavior of Cepheids that is revealed by their **light curves**.

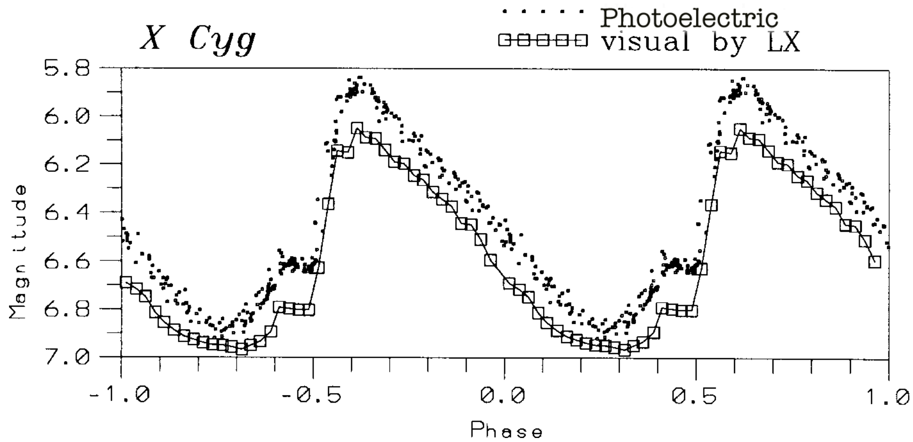
An example of this shows up in the analysis of SV Vul. The available photoelectric data set consisted of 164 data points spread over a 3000-day time span. The AAVSO visual data consisted of 6,217 total observations with continuous coverage for more than 10,000 days. Plotting the photoelectric data along with 1,634 data points from one of the AAVSO observers (OV) shows how important contributions of visual observations are to the study of variable stars. (See graph at the top of the following page.)



Such complete coverage over a long time span yields estimates for the period and amplitude which are more meaningful than those from available sparse photoelectric data. For example, the graph below shows that the period of SV Vul has undergone important changes over the last 10,000 days: increasing from **Julian Day** (JD) 2441000 to 2442000 and again from JD 2446000 to 2447000. It also shows a decrease from JD 2447000 to 2450000. These period changes are present in the visual data of both observers, but would not have been found from inspection of the available photoelectric data.



Not only can the period and amplitude be determined with great **accuracy**, but visual data can detect small, significant features in the shape of light curves. This is illustrated in the comparison of photoelectric and visual data for X Cyg in the following graph.

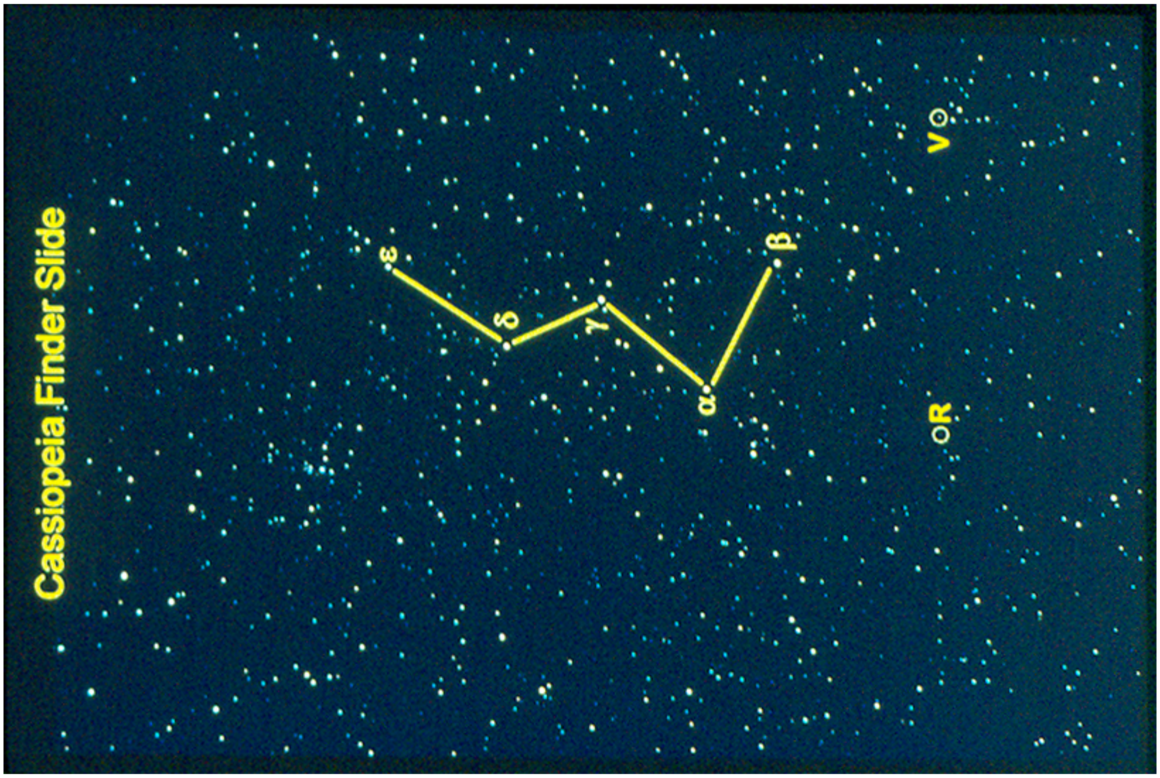


The prominent bump on the ascending branch of the light curve is clearly present in both the photoelectric and the visual data; there is also a very small bump near maximum, which is also present in both data sets, but much more clearly evident in the visual data of the amateur astronomer LX. The shape of the light curve, including small irregularities, can be detected just as well from the visual data as it can from the more precise photoelectric data. Visual observers can determine the period of a Cepheid variable with great accuracy. The photoelectric light curve is about 0.1 to 0.2 magnitude brighter than the visual light curve of LX. This is because the eye's response to light is not the same as a photoelectric photometer's. Any **random errors** of the observer are smoothed out by the large number of observations. However, with such small amplitude changes, any **systematic errors** will become evident.

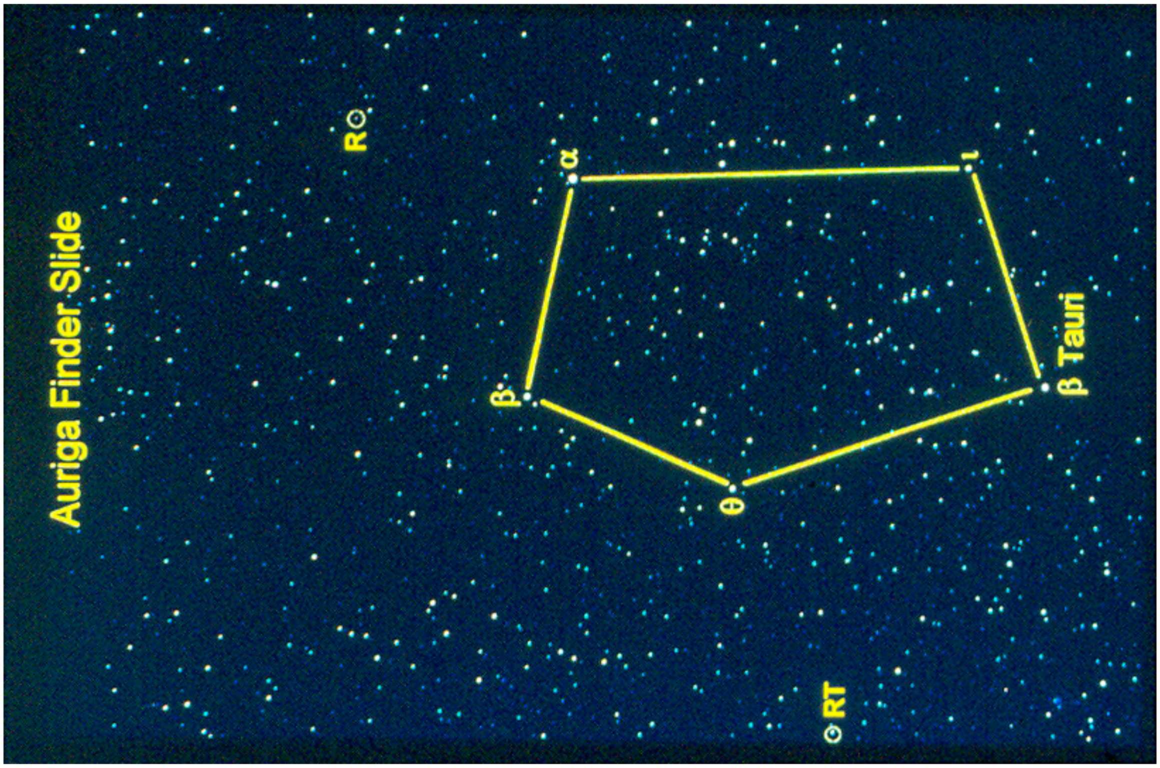
Foster's analysis of visual and available photoelectric data shows that visual data are good enough for serious study of Cepheids, alerting professional astronomers to amplitude changes, providing period estimates, and revealing the internal structure in the shape of light curves.

[Adapted from a presentation by Grant Foster at the 1997 AAVSO Spring Meeting in Sion, Switzerland. The paper was published in the proceedings of the meeting, entitled Variable Stars: New Frontiers.*]*

Slides for Core Activity 6.4 – p. 1/2



Slides for Core Activity 6.4 – p. 2/2



Chapter 6: Measuring Variable Stars Visually

Summary

This chapter is an introduction to identifying and making magnitude estimates of variable stars in the classroom, using the slide and print sets which accompany this curriculum. The activities in this chapter prepare students to make successful observations of variable stars in the real sky, and to perform an accurate analysis of their data.

Terminology

accuracy	interpolation	photometry	significant digits
amplitude	Julian Day	precision	systematic error
comparison stars	light curve	random error	trend
extrapolation	percent error	range	

Common Misconceptions

1. *All error is caused by "human" error.*
2. *Data that do not "fit" the line are wrong.*
3. *The only information on a graph is the data plotted.*

SUGGESTIONS FOR THE POSTER PAGES, INVESTIGATIONS, AND ACTIVITIES

Investigation 6.1: Interpolation

This is a simple but powerful activity if exploited to its full potential. The materials required are uncomplicated: a set of 10 cylinders of varying size, such as food and coffee cans, jars, tubes, and the like; and rulers, string, and graph paper. Provide some cylinders that are more difficult to measure due to their flexibility, such as paper towel tubes. This will add another dimension to the discussion of the results. Using the string to measure the circumference and then measuring the string with the ruler adds a further complication if students are not careful with their measurements. Each group of students needs to have the same set of cylinders and the same type of string in order to compare results.

Learning how to graph real data is a difficult activity for students who have never done so before: students think that their graphs should have the precision and exactness that occurs in the math classroom. Real information is frustrating—it often refuses to cooperate and line itself up properly. Learning how to interpret a trend, how to do the "best fit" curve, and what data are erroneous enough to leave out of the "best fit" is challenging. However, it is a vital and necessary skill for scientists to acquire, and worth the extra effort to learn.

Strongly emphasize to the students the importance of labeling the axes, making sure the proper units are attached, and determining an appropriate scale for the graph. The scale should allow the data points to cover the graph; the data should not be scrunched up in any one section of the graph, leaving large blank areas, or it will be harder to see the relationships. Also, data points should not fall directly on the axes. Students who have had some algebra can calculate the slope of the line, the specific relationship between the two variables being plotted. They are actually plotting C = d, which is a simple example of the straight line equation y = mx + b. Most students have difficulty recognizing this relationship outside of the mathematics classroom. The slope should be calculated from two values on the line which are *not* plotted values. Students should not get the mistaken impression that they can take two measurements for circumference and diameter and calculate the slope without doing any graphing. If one measurement is too imprecise, the results will be unreliable. A typical completed graph of this activity is included for your information (see opposite page).

NOTE: The students have been asked if they should remeasure or ignore what looks like a bad data set. Usually, in a situation where a measurement seems suspect, one will remeasure. This would be possible in any circumstance where the result is already known and students are determining their percent error—a measure of how precise their measurements were. In science, anomolous results are usually disregarded. After all, error cannot be eliminated. In variable star astronomy there is no way to remeasure, no way to go back in time to determine what was wrong. A magnitude estimation from an observer which radically differs from those of other observers made at the same time—after being checked for such problems as typographical errors—is flagged as being possibly erroneous. (See Poster Talk 13.2 for a discussion of the ways such errors are detected and corrected.) Although variable stars change in magnitude, every observer should see approximately the same magnitude at the same time for a star.

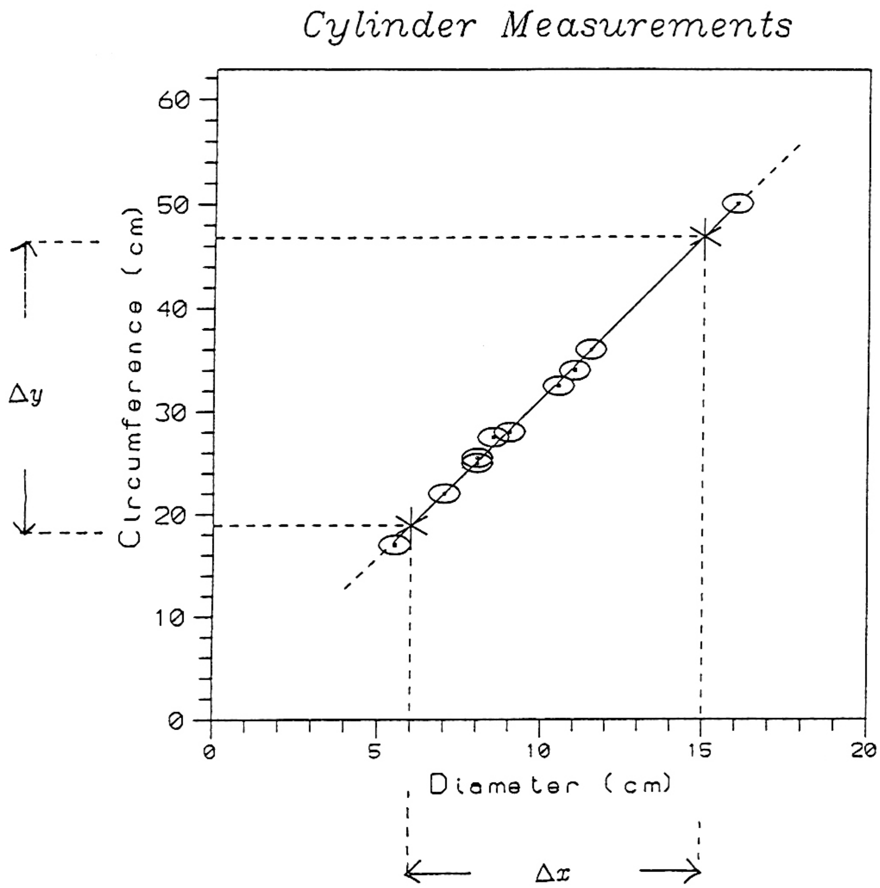
The following extensions are included in Investigation 6.3, although they could be addressed here as well, depending on the class.

Extensions

Calculating the percentage of error will tell the students how successfully they performed the measurements and determined the “best fit” curve (line). Having the students calculate the error for the entire classroom will give them solid proof that the more data points averaged, the smaller the percentage of error. The class average will be smaller than the individual averages. In variable star astronomy, the strength of the data depends upon the large number of observations. And of course, the purpose of this activity— interpolation—is important to both magnitude estimation and making best fit curves.

The students can also discuss random errors, and any systematic errors that might be inherent to this activity

Example of Completed Investigation 6.1 and Core Activity 6.3



$$C = \pi d$$

$$\pi = \frac{C}{d} = \frac{\Delta y}{\Delta x}$$

$$\Delta y = 46.8 - 18.9 = 27.9$$

$$\Delta x = 15 - 6 = 9$$

$$\text{estimated } \pi \approx \frac{27.9}{9} = 3.1$$

$$\text{true } \pi = 3.1416$$

$$\text{error } = \frac{3.1 - 3.1416}{3.1416} \times 100\% \approx -1\%$$

Core Activity 6.2: Estimating Magnitudes Using Interpolation

This is an extremely basic activity. Activity 6.4 is identical except that it uses real-sky images instead of paper charts. Depending on your class, you may use this as an activity or a demonstration to lead up to Activity 6.4, or leave it out altogether.

Core Activity 6.3: How Accurate Are Your Results?

Significant figures are not a favorite topic for students, but they are important in measuring. Students need to understand the difference between precision and accuracy, and at the least comprehend that when multiplying, dividing, adding, or subtracting numbers, the resulting answer is only as accurate as the least accurate measurement. The class should discuss here—whether for the first time or to reinforce a previous discussion—their results from the Investigation 6.1 graph; they should understand the difference between random and systematic error and recognize examples of each. The results should show that random errors will become insignificant when many data points are analyzed. Systematic errors are much more dangerous if they go undetected, as they will give inaccurate results.

Answers to Significant Digit Exercise

Exercise 5:		*Exercise 6:*
a) 3	f) 1	a) 72.6
b) 3	g) 6	b) 5.8
c) 2	h) 3	c) 181.9
d) 4	i) 5	d) 78.7 (=7.87×10^1)
e) 4	j) 4	

Poster Page: The Dangers of Radiation

As an extension or alternative classroom project, you can involve students in an active discussion on the observation of artificial satellites. The material requirements are minimal, and there is much to discuss. There is a huge array of satellites—from HST and Mir to weather and other Earth-observing satellites, and they have a variety of orbits, from horizontal or inclined to geostationary and polar. Students can focus on a satellite they know, time its appearances, and then predict future sightings. It is not a simple task. A satellite’s orbital plane does not remain fixed in space but rotates slowly about the Earth’s axis due to gravitational perturbations. The direction of drift is to the west if the satellite is traveling eastward, at a rate of up to 8^o per day, depending on the orbital inclination. The mass of the Earth controls the orbital period of a satellite. The Earth's gravity, gravitational perturbations, and the shape of the orbit all have an effect on the satellite's speed. Many physical laws are involved. There are several techniques for accurate visual observations of altitude, speed, rotation rate, and so on.

Core Activity 6.4: More Magnitude Estimations

Students will estimate magnitudes of the major star patterns for one or more constellations, given the brightest and dimmest stars for comparison. Practice with as many constellations as necessary for your class to become comfortable with their estimations. It will seem difficult at first, sometimes almost impossible; however, after a little practice it will become second nature. The magnitudes of all the bright stars within the constellations are listed in Core Activity 4.5: Constellation Plots.

Aur – 0.1 to 2.7
Cas – 2.2 to 3.4
Cep – 2.4 to 4.2
Cyg – 1.2 to 2.5
UMa – 1.8 to 3.3

HOA FUN

HOA Fun: You may elect to have your students use the HOA Fun software program included with this curriculum (see instructions in Appendix). It is designed as an introduction to observing variable stars over time and estimating their magnitudes. The program is not concerned with "accuracy"—there are no right or wrong answers. It is simply meant as a nonthreatening and entertaining look into the process of variable star astronomy.

Core Activity 6.5: Collecting Your Own Data

This activity involves estimating the magnitude of a single variable star, utilizing a paper starfield, as in Core Activity 6.2. For this activity, students are required to estimate the star's magnitude over time. The astronomical community uses the Julian Day (not to be confused with the Julian Calendar) as a unit of time. The students are given a brief description of what the Julian Day is and how it developed. An interesting discussion could be developed here about the topic of time. After all, what if suddenly eleven days were dropped from our calendar and the beginning of the year changed from January 1st to April 1st? What would be the consequences? Would landlords lose three-and-a-half months' rent? For almost 200 years Great Britain and America were out of sync with European calendar dates. Why did it last so long? Could that difference be maintained today? From sundials to atomic clocks, humanity has tried to simultaneously impose arbitrary timekeeping inventions on nature and use nature as clockwork. It has been an interesting and complicated business trying to keep time. You can get today's Julian Date (JD) from the JD calendar which comes with this curriculum.

Also included is Table 6.6, where the entire class can put their individual estimates together for group analysis. Assign each student an ID number using their initials, last name first (for example, Donna L. Young would become YDL). Have the students graph their data, either on the board or on a large piece of paper, or on an overhead transparency. Each student can use a different color and/or symbol to see how their estimates compare to their classmates. Have them draw in the “best fit” curve. Have the students keep their data sheets. The information in Table 6.6 will be used several times in Unit 5 for different types of data analysis.

Poster Page: Who Are the Amateur Astronomers?

HOA VIDEO

There are most probably amateur astronomers in your vicinity, or even amateur astronomy organizations. Amateur astronomers come from all occupations, and are enthusiastic about their hobby. You can learn more about them in the section of the HOA video entitled “Backyard Astronomy.” Locate an amateur astronomer who would like to come visit your classroom and share their experiences with your students. They may even assist you in your variable star observations. They will know the best viewing places and times, and have an excellent knowledge of the night sky. If you are unable to find an amateur astronomer, contact AAVSO Headquarters, and they may be able to locate one for you. What famous people in history have also been amateur astronomers? Just what do amateur astronomers do? Are there other ways in which they make significant contributions to astronomy besides variable star observations?

Core Activity 6.6: Magnitude Estimation and Graphing with Slides (and/or Prints)

RESOURCE

If your students are going to observe the real sky, this activity will help to ensure their success. If you do not have access to a dark sky, or if it is not possible for your class to observe at night, this will be the culminating observational activity. The slide set included with this curriculum is a sequence taken of the variable star W Cyg, over a time frame of about 150 days. The slides show almost the full range in magnitude for this star. The slides and finder charts are used in tandem to locate W Cyg and its comparison stars. Also included is a series of prints identical to the Cygnus and W Cyg slide sets. The slides can seem confusing at first; however, with practice your students will rapidly become more proficient in making magnitude estimates. The prints can also be used alongside the slides and finder charts. Only one set is provided; additional sets can be purchased from the AAVSO, or the prints can be adequately reproduced with a good color copier.

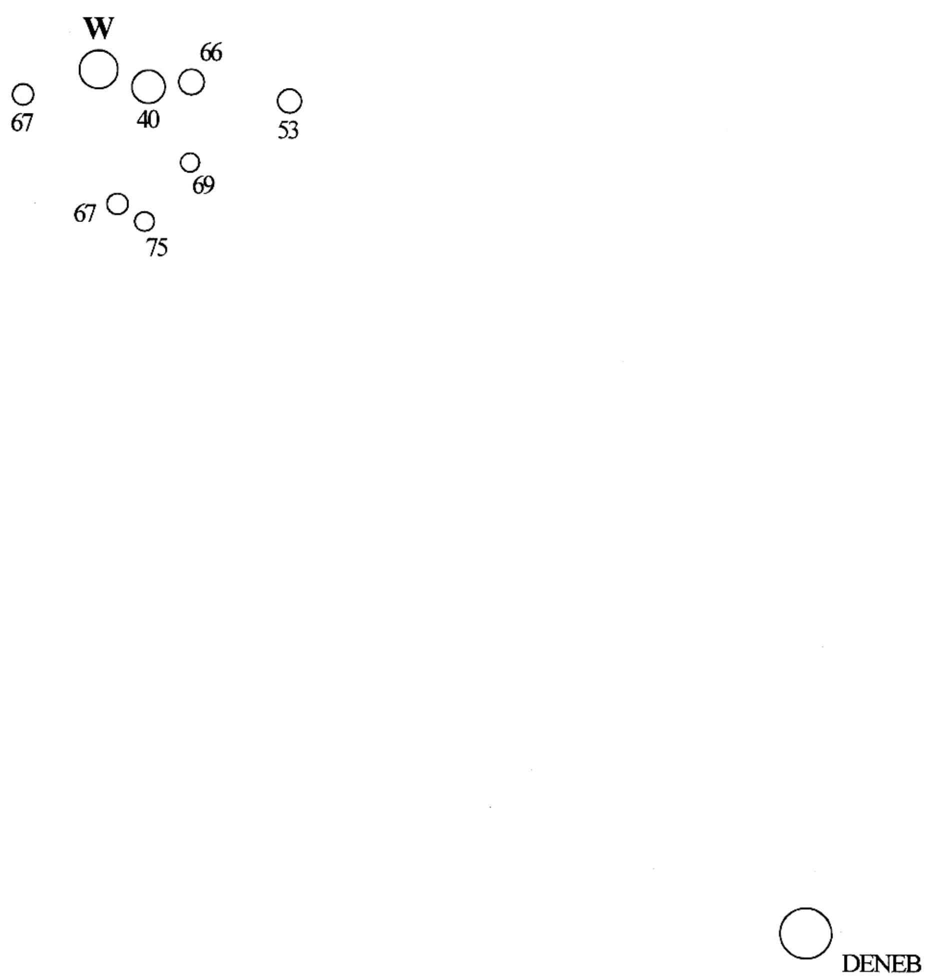
You will need to practice and become adept at estimation with the slides yourself before your students engage in this activity. The most difficult aspect of using the slides is locating the variable star and its comparison stars. Take as much time as possible to practice this until you nearly have the stars’ positions memorized. Three of the variable stars that are easiest to locate are W Cyg, chi Cyg, and R Aur. A slide of each of the HOA constellations is provided with the variable stars indicated.

It is also helpful to have students make their own transparency overlay for the prints, identifying W Cyg and the comparison stars, and labeling their magnitudes. Use a bright color, non-permanent pen or china marker (yellow or orange work well). Then the overlay can be moved from print to print as each successive slide is projected. NOTE: The star field will move around a little as you go from one print to another, as it is difficult for a photographer to set up in the exact same spot when photographing the sky several days apart. There are also other variable stars in Cygnus which you may want to use with the class for additional practice. They are indicated on the finder charts. A transparency master is included with the positions of variable star W Cyg and its comparison stars and their magnitudes. Chi Cyg is an excellent, and dramatic, example of a variable star. Its magnitude range is greater than that of W Cyg and is easy to estimate. It was not used as the prime variable star for this activity because it is a red star, which might make the activity more confusing for students (for most people, red objects in the night sky appear brighter than they really are).

W Cyg has a period of 131 days and a range in magnitude from 5.5 at maximum to 7.0 at minimum. The range that is covered with the series of slides is approximately the same range.

Chi Cyg has a period of 408 days and a range in magnitude from 4.3 at maximum to 14.1 at minimum. The range covered by the slides is approximately 5.6 to 10.4.

Transparency Master for Overlay of W Cyg Field Prints



Chapter 7: Observing Variable Stars in the Real Sky

Introduction

Every night hundreds of amateur astronomers around the world look at the night sky from their backyards, just as you are now preparing to do. Stargazers contemplate the splendor and poetry of the dancing jewels above them, and feel serene within the solitude of night and the constancy of the universe. Amateur astronomers, too, appreciate the wonders of the stars; however, they also know that the stars are not constant, but vary in their brightness. So they observe them systematically, filling their logbooks with data which they plot and analyze. They not only want to enjoy the stars, but want to investigate and analyze their behavior and share their findings with other astronomers around the world. Amateur astronomers do not feel alone in the darkness. They know they have nighttime companions with a similar mission: to become intimately acquainted with stellar behavior, to decode the messages from variable stars. So when you go out to your backyard and begin your quest, remember that there are many eyes observing the heavens along with you.

There are over 30,000 stars known to be changing in brightness and another 14,000 stars suspected to be changing in brightness. These known and suspected variable stars require continual, systematic observation over decades to determine their short-term and long-term behavior, and to catch and record any unusual activity. During the last two decades, variable stars have been closely monitored using specialized instruments on large ground-based telescopes, and x-ray, ultraviolet, and infrared detectors aboard satellites. It is essential to have ongoing visual data from amateur astronomers to correlate with the multi-wavelength observations these specialized instruments obtain.

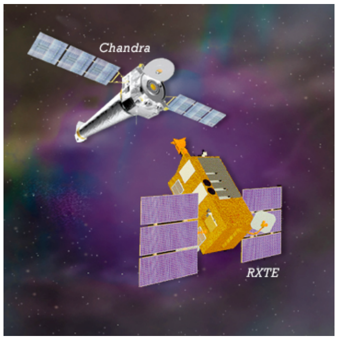
For three-and-a-half years the *HIPPARCOS* satellite measured the distances to stars within 500 light-years of the Sun with incredible precision. The satellite also measured the magnitudes of several thousand variable stars, some with very large fluctuations between their brightest and dimmest phases. Because the dimmer the star the longer the satellite had to point at it, the HIPPARCOS team had to know exactly where the star was in its magnitude cycle in order to allow enough time to gather the necessary data. For many variable stars, this behavior is unpredictable. Here is an example of where the amateur astronomer's work is so vital. Groups of amateurs have long been members of various variable star organizations around the world, such as the *American Association of Variable Star Observers (AAVSO)* in Cambridge, Massachusetts. As the HIPPARCOS satellite orbited Earth, these amateur observers sent more than 6,000 observations a month of specific variable stars to AAVSO headquarters. The AAVSO director used these observations to help the HIPPARCOS astronomers predict the brightness of these stars at any time during the mission. This collaboration between amateurs and professionals enabled the HIPPARCOS scientists to collect crucial data on some of the most intriguing variable stars in the sky. High-tech instruments have an extreme degree of precision, but amateurs compensate for their lower degree of precision by the sheer volume of data they produce. Amateurs also are able to watch variables over long periods of time—crucial to determining the light curves for long-period stars. This contrasts with the short observing times allotted to the many professional astronomers who want to access satellites such as HIPPARCOS, or ground-based telescopes at large observatories around the world. Both amateurs and professionals play a vital role in variable star astronomy.

The full scientific impact of the HIPPARCOS mission is only beginning to be gauged. One of the most inspirational aspects of this effort is the staggering degree of human cooperation required, from space agencies such as the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA), to HIPPARCOS' science teams, to many variable star organizations, to the not-so-lonely amateur astronomer surveying the heavens from his or her backyard.

The significance of amateurs' contributions to astronomy was first realized 150 years ago by Friedrich Argelander, a German astronomer who is considered to be the father of variable star astronomy. In 1844, when only 30 variable stars were known, he wrote the following:

> *I lay these hitherto sorely neglected variables most pressingly on the heart of all lovers of the starry heavens. May you increase your enjoyment by combining the useful and the pleasant while you perform an important part towards the increase of human knowledge.*

You now have the basic tools, knowledge, and skills necessary to begin observing variable stars. Perhaps one day your observations will be in the AAVSO International Database, assisting professional astronomers in their unceasing scrutiny of the universe.



HIPPARCOS is not the only scientific mission that has teamed up with the AAVSO observers. The Chandra X-Ray Observatory is the most sophisticated X-ray observatory launched by NASA. Chandra is designed to observe X-rays from high-energy regions of the universe, such as X-ray binary stars. Chandra, the Extreme UltraViolet Explorer (EUVE), and the Rossi X-ray Timing Explorer (RXTE) provided an opportunity for observational collaborations with members of AAVSO. For years, amateur astronomers have informed professional scientists of novae, supernovae and other cataclysmic events. The cooperation between an organized group of dedicated amateur astronomers, and the professional astrophysicists who need these observations, is now quite finely tuned. When scientists are in need of ground-based observations to follow simultaneous satellite observations, they know that the AAVSO worldwide network of amateurs can be depended upon for fast, efficient, and reliable results. The Chandra Chronicles describe the fascinating process involved with the two observation projects. The Chronicles can be accessed at http://chandra.harvard.edu/chronicle/0300/aavso.html and http://chandra.harvard.edu/chronicle/0101/aavso.html .

Initial Preparations

These preparations should be followed for every observing session.

A. Choose the variable star(s) you will be observing. Determine with your planisphere if the constellation in which the star is located will be well-placed for observation on the day and time you plan to observe.

B. Using the AAVSO *finder* charts, determine the exact location of the variable, and the location and magnitudes of the comparison stars.

C. Do not observe alone—bring someone with you. Find a safe location that is as dark as possible and unobstructed by trees or buildings. Wear sunglasses indoors for 10 minutes or give yourself 15 to 20 minutes outside before you observe to allow your eyes to adjust to the darkness. Avoid street lights, yard lights, or automobile headlights, since a moment of exposure to any bright light destroys your darkness adaptation and you will have to wait 10–15 minutes for your eyes to become reaccustomed to the dark.

D. Check the latest weather conditions or forecast for the night you plan to observe. Do not do your observing when cirrus clouds are present because it is difficult to tell when they cover part of your view. Use your *Sky Gazer's Almanac* to determine the phase and rise/set time for the Moon to make sure it will not interfere with your viewing. Also check the almanac for other celestial events that will be taking place in the sky that you might not want to miss.

E. If you are not observing with the unaided eye, then familiarize yourself with the adjustments of the binoculars you are using. Have a logbook and pencil ready to record observations. A sample entry page is included which illustrates the necessary information to record (see next page). Carrying a dim red light, or a flashlight covered by a red filter is essential. The red light will allow you to read the charts and record your data without destroying your darkness adaptation.

F. Dress appropriately, especially if it is cool. It can be quite uncomfortable working with binoculars if you are cold. An air mattress, a lounge chair, or other comfortable chair is very practical. Observing while reclining, rather than standing or sitting, will help prevent you from having sore neck muscles. Make yourself as comfortable as possible for maximum viewing time.

The AAVSO Report Form (a sample of the front is shown here). Use this form to report observations of variable stars to the AAVSO.

THE AMERICAN ASSOCIATION OF VARIABLE STAR OBSERVERS
25 Birch Street, Cambridge, MA 02138, USA

VARIABLE STAR OBSERVATIONS

Sheet ________ of _________ Report No. _________

For Month of ___________________ Year _____________

Observer ____

Street ____

City _____________________ State ________________

Country ___________________ Zip Code ______________

Time Used, GMAT or ______________________________

Instrument(s) ____________________________________

AAVSO Observer Initials

____

For AAVSO HQ Use Only

Received ________________

Entered ________________

Verified ________________

Designation	Variable	JD & Decimal	Mag.	Key* &	Remarks	Comp. Stars	Chart and Date
					Total Number Observations Reported		

* KEY field contains AAVSO-selected one-letter abbreviations for REMARKS. Obtain list from AAVSO Headquarters or web site.

(turn sheet over)

The AAVSO Report Form (a sample of the back is shown here). Use this form to report observations of variable stars to the AAVSO.

AMERICAN ASSOCIATION OF VARIABLE STAR OBSERVERS
25 Birch Street,
Cambridge, MA 02138 USA

Observer____________________
For Month of ______________ Year __________

*Explanation of Key field characters

IMPORTANT—If an observation is uncertain, please put this character : [a colon] immediately after the magnitude. Each time you use the : character, please be sure to include the reason(s) for the uncertainty in the Remarks field and the appropriate one-letter character(s) in the Key field. This will maximize the amount of information contained in your observations, as well as assist the AAVSO in its record-keeping.

The Key field is for AAVSO-selected one-letter abbreviations of comments about an observation, or for multi-letter abbreviations describing instrumentation such as PEP or CCD. The complete list of all these abbreviations may be obtained from AAVSO Headquarters or fromthe AAVSO web site (http://www.aavso.org). Use as many letters as needed for an observation. Even if there is no uncertainty, please use these letter characters whenever you choose to make a remark about any observation. (However, please do NOT use : if there is no uncertainty.) If you do not wish to make any remarks, please leave the Key & Remarks field blank.

AAVSO Observer Initials

____

For AAVSO HQ Use Only
Received __________
Entered __________
Verified __________

Designation	Variable	JD & Decimal	Mag.	Key* &	Remarks	Comp. Stars	Chart and Date
					Total Number Observations Reported		

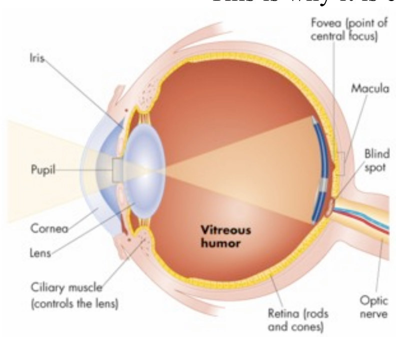
* KEY field contains AAVSO-selected one-letter abbreviations for REMARKS. Obtain list from AAVSO Headquarters or web site.

(turn sheet over)

Starlight in Your Eyes

The human eye resembles a camera. The eye is equipped with a built-in cleaning and lubricating system, an exposure meter, an automatic field finder, and a continuous supply of film. Light from an object enters the cornea, a transparent covering over the surface of the eye, and passes through a transparent lens held in place by ciliary muscles. An iris in front of the lens opens or closes like the shutter on a camera to regulate the amount of light entering the eye by involuntarily shrinking or dilating the pupil. The iris gradually constricts with age. Children and young adults have pupils that can open to 7 or 8 mm in diameter or larger, but by the age of 50 it is not unusual for the maximum pupil size to shrink to 5 mm, greatly reducing the amount of light-gathering capability of the eye. The cornea and lens together act as a lens of variable focal length that focuses light from an object to form a real image on the back surface of the eye, called the retina. Because the pupil size shrinks with age, the retina of a 60-year-old person receives about one-third as much light as does that of someone who is 30.

The retina acts like the film of a camera. It contains about 130 million light-sensitive cells called cones and rods. Light absorbed by these cells initiates photochemical reactions that create electrical impulses in nerves attached to the cones and rods. The signals from individual cones and rods are combined in a complicated network of nerve cells and transferred from the eye to the brain via the optic nerve. What we see depends on which cones and rods are excited by absorbing light, and the way in which the electrical signals from different cones and rods are combined and interpreted by the brain. Our eyes do a lot of "thinking" about what information gets sent and what gets discarded.



The cones are concentrated in one part of the retina called the fovea. The fovea is about 0.3 mm in diameter and contains 10,000 cones and no rods. Each cone in this region has a separate nerve fiber that leads to the brain along the optic nerve. Because of the large number of nerves coming from this small area, the fovea is the best part of the retina for resolving the fine details of a bright object. Besides providing a region of high visual acuity, the cones in the fovea and in other parts of the retina are specialized for detecting different colors of light. The ability to "see" the colors of stars is greatly reduced because the intensity of the colors is not great enough to stimulate the cones. Another reason is that the transparency of the lens decreases with age. Babies have very transparent lenses that pass wavelengths of light down to 3500Å in the deep violet.

The concentration of cones decreases outside the fovea. In these peripheral regions, the rods predominate. Their density in the retina (~150,000/m^2) is about the same as that of the cones in the fovea region. However, the light signals from perhaps 100 adjacent rods are brought together into a single nerve cell that leads to the brain. This combining of the rod signals reduces our ability to see the fine details of an object but helps us see dimly lit objects, since many small signals are combined to produce a larger signal. This is why it is easier to estimate the magnitude of a dim variable star by using a technique called "averted vision," i.e., not looking directly at the star, but to one side of the star.

A normal eye can focus on objects located anywhere from about 25 cm to hundreds of miles away. This ability to focus on objects at different distances is called accommodation. Unlike the camera, which uses a fixed focal length lens and a variable image distance to accommodate different object distances, the eye has a fixed image distance of about 2.1 cm (the distance from the cornea and lens to the retina) and a variable focal length lens system.

When the eye looks at distant objects, the ciliary muscle attached to the lens of the eye relaxes, and the lens becomes less curved. When less curved, the focal length increases and an image is formed at the retina. If the lens remains flattened and the object moves closer to the lens, the image will then move back behind the retina, causing a blurred pattern of light on the retina. To avoid this, the ciliary muscles contract and cause an increase in the curvature of the lens, reducing its focal length. With reduced focal length, the image moves forward and again forms a sharp, focused image on the retina. If your eyes become tired after reading for many hours, it is because the ciliary muscles have been tensed to keep the lenses of your eyes curved.

The far point of the eye is the greatest distance to an object on which the relaxed eye can focus. The near point of the eye is the closest distance of an object on which the tensed eye can focus. For the normal eye, the far point is effectively infinity (we can focus on the Moon and distant stars) and the near point is about 25 to 50 cm. This variable "zoom lens" changes with age and the minimum focus distance changes until it is difficult to focus on objects even 20 cm away, making charts and instruments difficult to read. The aging eye gradually alters the way we perceive the universe.

The aperture is the clear diameter of the objective lens in a refracting telescope or of the primary mirror in a reflecting telescope. As the aperture is increased, the telescope gathers more light, and so will discern fainter objects: the light-gathering power depends on area (i.e., the square of the aperture). The aperture ratio is the ratio d/f of the effective diameter (aperture), d, of a lens or mirror to its focal length, f. In near-total darkness, the pupil of the human eye expands to its greatest diameter in an attempt to collect as much light as possible. The fully expanded pupil of the human eye is ~7 mm. Telescopes have a ratio of magnification to aperture that yield a 7 mm exit pupil to match and fill with starlight the fully expanded pupil of the human eye. However, there is a range of expanded pupil sizes. Studies have shown that even at the age of 15, when pupil size tends to peak, individual values range from 5 mm to 9 mm. And after age 30, it's mostly downhill. To maximize light-gathering capability, older people need to have larger telescope apertures, and everyone should have their dark-adapted pupil size measured and choose the magnification that will optimize the exit pupil of the eyepiece.

How might differences in eyes have affected early astronomers, such as the Mayans, American Indians, Chinese, Babylonian, and Egyptians? What age were the observers? What kind of eyesight did they have? When were vision problems discovered? When were corrective procedures developed, such as lenses and glasses? Galileo lost his sight for a week after observing sunspots with a telescope. In early days of telescope use, smoked glass was used as a protective filter. Such a filter is ineffective against damaging UV radiation. Why? Did Galileo's observations eventually lead to the glaucoma that greatly reduced the vision in his right eye and blinded the left? Johannes Kepler, the first person to understand the function of the eye's light-sensitive retina, was myopic and suffered from severe astigmatism. How would this interfere with what he saw in the night sky? Can excessive exposure to ultraviolet light cause long-term damage to the eye? Did other famous astronomers have vision problems?

Dresden Codex,
detailing Mayan astronomical observations

Occupational Hazards of the Variable Star Observer

The following stories were shared in the AAVSO on-line discussion group, and were subsequently printed in AAVSO Newsletter No. 19 as part of the Observers' Forum feature.

Dave Sworin (California):

I visited my dermatologist today... I took the opportunity to ask him about my hands, which have gotten pretty raw after a full night of observing. He suggested that my hands are losing moisture in the cool dry air at night in the open, and that I should try various kinds of creams or lotions.... I explained that I'm handling optics (that means Nagler eyepieces in case you were wondering), and that I did not want to get any junk on my eyepieces. At any rate I have something to try.

It occurred to me that perhaps Variable Star Observing has its own set of "occupational" hazards. ...Here is a list of physical problems I have run into while observing:

1. Raw finger and thumb from turning focuser all night.
2. Mosquito bites on hands, arms, face, and neck.
3. Tired back from observing in awkward positions.
4. Eye inflammation possibly picked up from eyepiece sharing with another amateur.

Have you run into others or had similar experiences?

Georg Comello (The Netherlands):

Yes, I had some physical problems too while variable star observing. They are a little bit different from those of Dave Sworin.

1. In 1963 my eyebrow froze to the eyepiece of the finder at -19.5°C.
2. Once I fell off the observing ladder while looking for T Dra with the 6-inch refractor. There is still blood on the chart of this Mira star.
3. A few years ago I slipped on a snail in the garden while observing with the transportable C8, and hurt my leg.
4. The neighbor's cat once was pursuing a competitor, while I was estimating R Crv with the portable telescope in the garden. She hit my leg and the tripod. No damage occurred. So observing variable stars can be quite dangerous....

Gary Poyner (England):

In 1982 I had an eyepiece stick to my eye in -18 degrees temperature. Very painful! Also in September 1996 my aluminum stepladder broke in the observatory whilst I was on the top step! This resulted in quite serious damage to my left leg and back. Ruined my night that did (and it was very clear too!).

One other story. Not so much physical problems but interesting to relate. I was returning from a Variable Star Section meeting in November 1981 with four others, when we were stopped by no less than SEVEN police cars, and arrested for armed robbery of a bank. It appears that our car was stolen during the day, and returned to the same place after taking part in the robbery. At the end of the meeting we innocently returned to the car which was under surveillance by the police. We were all locked up until we could prove where we had been that day (which was no problem because we had about 60 witnesses).

Rik Hill (Arizona):

1. I had a counterweight slide off my mount and land on my big toe, busting it. There's still blood in the cement!
2. Back in '76 I was carrying out an RV-6 telescope, looked up to see if it was still clear, and completely missed the porch steps. That resulted in torn ligaments, but the telescope is fine.

Jerry McKenna (New Jersey):

I must tell about two of my local hazards:

1. Skunks. Some years ago there was an outburst of UV Per that was best visible from the front of the house. At 2:30 a.m. I was carrying my 8" Celestron from its normal station in the rear to the front. While I was setting up the telescope a skunk crossed my path. ... I made a quick observation and pulled my telescope away. My own neighborhood has been favored by skunks all of my life.

2. Tires. I live at the base of a hill. Until recently we were allowed to throw used tires out with the trash. Several times in the last 20 years tires have come crashing down. One has crashed into my front door; several have crashed into the rear of my property. It is only luck that my telescope has not been hit.

Dan Kaiser (Indiana):

...Below is an excerpt from a letter I wrote the following day after my own personal `CLOSE ENCOUNTER.' What follows is a TRUE story! It really happened!

17 July, 1990. Last night, around midnight, I was at my primary observing site, my backyard. I was busy taking photographs with my camera piggybacked on a C-8 telescope.

I had also set up a second telescope so that I could do some visual work simultaneously. While making variable star estimates with the second telescope my kitchen timer rang, indicating it was time to end an exposure. As I approached the C-8, I was startled to see what at first appeared to be a very large object hovering almost directly overhead.

It was oval in shape and very dark, making what looked like a hole in the starry sky overhead. After a few moments I realized it was not big and far away, but small and near, perhaps 20 feet directly above my telescope. It seemed to be just floating there.

I circled around the C-8 to approach from another direction. This is when I noticed that it was descending, very slowly. I stopped and watched as it gently came lower and lower. After maybe 45 seconds, it finally stopped about 3 feet above the ground and maybe 6 feet from the C-8. It just hovered there. I had no idea what it was, and quite frankly was apprehensive about approaching it.

Another minute went by. The unidentified flying object still hovered three feet off the ground. When it failed to move any more I stepped closer. I turned on my flashlight, but it being a red light I could not really see well. I had to get close before I could see clearly. There, on the side of my mystery object, I could make out lettering! It read "Wikes Lumber Co." It was then that I realized it was a balloon! It wasn't until I came even closer that I saw the string hanging down to the ground. The weight of the string must have pulled it down through the calm air until it touched ground, at which time it no longer weighed enough to pull the balloon all the way to the ground.

Sometimes I wonder, "What are the odds of a balloon coming down, in the middle of the night, right next to a sky gazer and his telescope?"

One more occupational hazard. When I was not quite 12, I was looking forward to the solar eclipse of July 20, 1963. I had recently gotten an Edmund 3" reflecting telescope. In preparation for the big day I tried out various ways of possible solar viewing. ... Edmund recommended solar projection, using an oatmeal carton. Of course, I was too impatient to do it the right way. I tried to view the Sun with a thick layer of photographic negatives. It only took a few seconds for me to hear a crackling sound. Luckily for me I never actually looked at the Sun. I implored my mother to save the next oatmeal box for me.

David B. Williams (Indiana)

While observing a visual minimum of eclipsing binary Y Leonis from a national park in Arizona, I had a skunk wander over and stick its nose up my pant leg. I heard something snuffling along the ground and looked down. Fortunately, there was a quarter moon, which offered enough light at the otherwise black site so that I could see the double white stripe moving toward me. It wasn't cold, but this was a situation in which I froze to the eyepiece too!

Core Activity 7.1: Observing Your First Variable Star—Delta Cephei

From most latitudes in the northern hemisphere in the autumn, delta Cep is bright and high in the sky—away from the horizon and local light pollution. It is outside the Milky Way and in a fairly dark and uncluttered region of the sky.

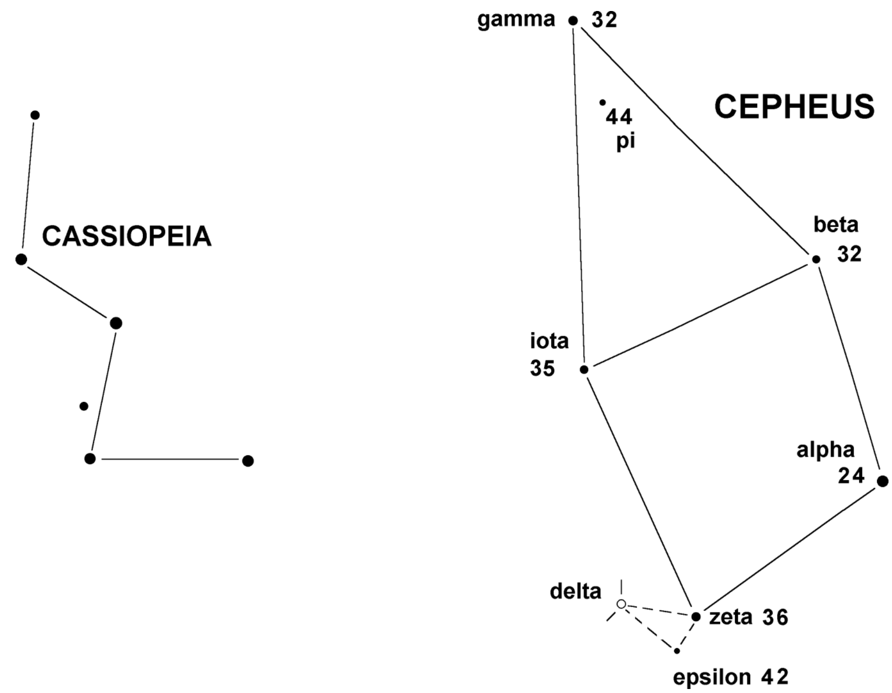


Figure 7.1

1. Enter in your logbook the name of the star (delta Cephei), the date of the observing session and the hour (later you will enter the minutes to the nearest quarter hour).

2. Using your planisphere or star charts, find the Big Dipper and Polaris using the pointer stars.

3. "Star hop" to Cassiopeia and then to Cepheus (Figure 7.1 above).

4. Find the group of three stars near one corner of the rectangular portion of Cepheus. Here is delta Cephei and its comparison stars zeta Cephei (magnitude 3.6) and epsilon Cephei (magnitude 4.2). This is the most difficult part and may take you several attempts, as you alternately look at the chart (Figure 7.1) and the sky.

5. Using averted vision, observe the variable star and its comparison stars at the center of your field of view. Averted vision is a technique in which you orient the star at the center of your field of view, and then gaze at the edge of the field.

Peripheral vision is more sensitive to black and white, so the difference in magnitude will be easier to discern.

6. Estimate your variable star's magnitude to the nearest tenth by using the nearby comparison stars. Look quickly back and forth and ask yourself: Is it dimmer or brighter than this comparison star? Is it dimmer or brighter than the second comparison star? If it is brighter, by how many tenths? Make a note of it. Then estimate the magnitude of your variable star again, and do it a third time. Enter the three numbers and average them in your logbook; then record your result in the data table.

7. Record the names and magnitudes of the comparison stars used.

8. Record the time of your observation to the nearest quarter hour.

9. Place a colon [:] after your observation if you are unsure of your observations due to a bright Moon or possible cirrus clouds. Do not be discouraged if you initially cannot tell the difference between a star of 3.0 and 3.5 in magnitude. Remember, your observations are a valuable "part of the whole" even if you are not yet an expert observer. With experience, you will be able to make your observations much more accurately and quickly.

10. After observing, calculate the Julian Date (JD), and record it in your log book. The Julian day runs from noon to noon, so you will have to convert your observation time to the fraction of the day starting from noon. Use the following steps to convert to the Julian Date:

    a. Convert the quarter of the hour to a decimal as follows. An observation time of 9:45 is 9.75 hr (45 minutes is 75% of an hour); an observation time of 2:15 is 2.25 hr (15 minutes is 25% of an hour); an observation time of 5:30 is 5.50 hr (30 minutes is 50% of an hour).

    b. Convert your time of observation to Greenwich Mean Astronomical Time (GMAT) (the starting time of the day for astronomers) by taking the time from (a) above and:

       During Daylight Savings Time:

       - adding 4 hours in the Eastern Time Zone (EDT)
       - adding 5 hours in the Central Time Zone (CDT)
       - adding 6 hours in the Mountain Time Zone (MDT)
       - adding 7 hours in the Pacific Time Zone (PDT)

During Standard Time:

- adding 5 hours in the Eastern Time Zone (EST)
- adding 6 hours in the Central Time Zone (CST)
- adding 7 hours in the Mountain Time Zone (MST)
- adding 8 hours in the Pacific Time Zone (PST)

For example, using the 9.75 hr from part (a) above, an observation taken during Eastern Daylight Savings Time would add 4 hours, therefore 9.75 + 4 = 13.75.

c. Convert this time [the number from (b) above] to the fraction of the day by dividing the time by 24; 13.75 divided by 24 = 0.57 or 0.6.

d. Look up the Julian day for the date of your observation from the Julian day calendar provided. For example, July 28th, 1995, is 2,440,000 + 9927 = 2449927.

Adding the result from (c) above, the JD = 2449927.6.

To summarize the above example for a magnitude estimation of delta Cep at 9:45 PM on July 28, 1995, in Boston, MA:

1. 9:45 PM = 9.75 hr;
2. You are on EDT, so add 4 hours: 9.75 + 4 = 13.75;
3. Convert to fraction of the day: 13.75 hr divided by 24hr/day = 0.57 = 0.6;
4. July 28 is 2,449,927 on the JD calendar. Add the fraction of the day: 2449927 + 0.6 = 2449927.6.

Julian Day tables are provided. They give the Julian Day (JD) number for the zero day of every month from 1951 through 2050 (see Julian Day chart on the next page). For example, the JD for January 0, 1951, is 2433647. If you want the JD for January 10, simply add 10 to 2433647; the JD for January 10, 1951, is 2433657.

11. Observe delta Cep on every night possible for the next month. If you wish to have a more complete light curve, observe it twice a night with 3 hours between each observation. You may decide to plot your data on a graph and calculate the period of delta Cep. Your instructor will give you the actual period of this variable and you can determine how closely your results agree with the accepted value. In the following chapters you will learn how to further analyze your results mathematically.

Using the Julian Day Tables

The next page contains a table giving the Julian Days from 1951 to the year 2000, and on the reverse side the Julian Days from 2001 to 2050.

You will note that the start of each month is not indicated by 1 (such as January 1), but rather with zero (e.g., January 0). This means that January 0 is actually December 31 of the previous year. This numbering convention is used so that you can easily determine the Julian Date for any particular date in a month simply by adding the number of days to the zero date for that month. For example, the Julian Date for January 8, 1996, is:

Julian Date for January 0, 1996 = 2450083 + 8 (days) = 2450091

Julian Day Numbers 1996-2025

To use this table, add the calendar date (based on the noon to noon astronomical time) of your observation to the zero day of the appropriate month for the desired year. For example, for an observation made on February 6, 2015, the Julian date would be: 2457054 + 6 = 2457060.

Year	Jan 0	Feb 0	Mar 0	Apr 0	May 0	Jun 0	Jul 0	Aug 0	Sep 0	Oct 0	Nov 0	Dec 0
1996	2450083	2450114	2450143	2450174	2450204	2450235	2450265	2450296	2450327	2450357	2450388	2450418
1997	2450449	2450480	2450508	2450539	2450569	2450600	2450630	2450661	2450692	2450722	2450753	2450783
1998	2450814	2450845	2450873	2450904	2450934	2450965	2450995	2451026	2451057	2451087	2451118	2451148
1999	2451179	2451210	2451238	2451269	2451299	2451330	2451360	2451391	2451422	2451452	2451483	2451513
2000	2451544	2451575	2451604	2451635	2451665	2451696	2451726	2451757	2451788	2451818	2451849	2451879
2001	2451910	2451941	2451969	2452000	2452030	2452061	2452091	2452122	2452153	2452183	2452214	2452244
2002	2452275	2452306	2452334	2452365	2452395	2452426	2452456	2452487	2452518	2452548	2452579	2452609
2003	2452640	2452671	2452699	2452730	2452760	2452791	2452821	2452852	2452883	2452913	2452944	2452974
2004	2453005	2453036	2453065	2453096	2453126	2453157	2453187	2453218	2453249	2453279	2453310	2453340
2005	2453371	2453402	2453430	2453461	2453491	2453522	2453552	2453583	2453614	2453644	2453675	2453705
2006	2453736	2453767	2453795	2453826	2453856	2453887	2453917	2453948	2453979	2454009	2454040	2454070
2007	2454101	2454132	2454160	2454191	2454221	2454252	2454282	2454313	2454344	2454374	2454405	2454435
2008	2454466	2454497	2454526	2454557	2454587	2454618	2454648	2454679	2454710	2454740	2454771	2454801
2009	2454832	2454863	2454891	2454922	2454952	2454983	2455013	2455044	2455075	2455105	2455136	2455166
2010	2455197	2455228	2455256	2455287	2455317	2455348	2455378	2455409	2455440	2455470	2455501	2455531
2011	2455562	2455593	2455621	2455652	2455682	2455713	2455743	2455774	2455805	2455835	2455866	2455896
2012	2455927	2455958	2455987	2456018	2456048	2456079	2456109	2456140	2456171	2456201	2456232	2456262
2013	2456293	2456324	2456352	2456383	2456413	2456444	2456474	2456505	2456536	2456566	2456597	2456627
2014	2456658	2456689	2456717	2456748	2456778	2456809	2456839	2456870	2456901	2456931	2456962	2456992
2015	2457023	2457054	2457082	2457113	2457143	2457174	2457204	2457235	2457266	2457296	2457327	2457357
2016	2457388	2457419	2457448	2457479	2457509	2457540	2457570	2457601	2457632	2457662	2457693	2457723
2017	2457754	2457785	2457813	2457844	2457874	2457905	2457935	2457966	2457997	2458027	2458058	2458088
2018	2458119	2458150	2458178	2458209	2458239	2458270	2458300	2458331	2458362	2458392	2458423	2458453
2019	2458484	2458515	2458543	2458574	2458604	2458635	2458665	2458696	2458727	2458757	2458788	2458818
2020	2458849	2458880	2458909	2458940	2458970	2459001	2459031	2459062	2459093	2459123	2459154	2459184
2021	2459215	2459246	2459274	2459305	2459335	2459366	2459396	2459427	2459458	2459488	2459519	2459549
2022	2459580	2459611	2459639	2459670	2459700	2459731	2459761	2459792	2459823	2459853	2459884	2459914
2023	2459945	2459976	2460004	2460035	2460065	2460096	2460126	2460157	2460188	2460218	2460249	2460279
2024	2460310	2460341	2460370	2460401	2460431	2460462	2460492	2460523	2460554	2460584	2460615	2460645
2025	2460676	2460707	2460735	2460766	2460796	2460827	2460857	2460888	2460919	2460949	2460980	2461010

She Discovered How to Calculate the Distances to Galaxies

Henrietta Swan Leavitt (1868-1921) was born in Lancaster, Massachusetts and graduated from Radcliffe College in 1892. In 1902 she became a permanent staff member of the Harvard College Observatory. She soon rose "by her scientific ability and intense application" to head the department of photographic stellar photometry.

She spent a great deal of time searching Harvard photographic plates for variable stars in the Magellanic Clouds. Using a laborious process called superposition, in 1904 she discovered 152 variables in the Large Magellanic Cloud (LMC), and 59 in the Small Magellanic Cloud (SMC). The next year she reported 843 new variables in the SMC. These discoveries led Charles Young of Princeton to remark in a letter to HCO director E. C. Pickering, "What a variable-star `fiend' Miss Leavitt is-one can't keep up with the roll of the new discoveries."

Leavitt's greatest discovery came from her study of 1777 variable stars in the Magellanic Clouds. She was able to determine the periods of 25 Cepheid variables in the SMC and in 1912 announced what has since become known as the famous Period-Luminosity relation: "A straight line can be readily drawn among each of the two series of points corresponding to maxima and minima, thus showing that there is a simple relation between the brightness of the variable and their periods." Leavitt also realized that "since the variables are probably nearly the same distance from the earth, their periods are apparently associated with their actual emission of light, as determined by their mass, density, and surface brightness." Today the Period Luminosity relation is one of the backbones of the "distance ladder" used to calculate the distances to galaxies.

In the course of her work, Leavitt discovered four novae and about 2400 variables-about half of all the variable stars then known to exist. She also studied Algol-type eclipsing binaries and asteroids. She was a member of Phi Beta Kappa, the American Association of University Women, the American Astronomical and Astrophysical Society) the American Association for the Advancement of Science, and an honorary member of the American Association of Variable Star Observers. Unfortunately, she died young of cancer before her work on a new photographic magnitude scale could be completed. Her death was viewed as a "near calamity" by her colleagues. Her important contribution to scientific advancement was internationally acknowledged when, in 1925, the Swedish Academy of Sciences nominated her for the Nobel Prize.

Miss Leavitt inherited in a somewhat chastened form the stern virtues of her puritan ancestors. She took life seriously. Her sense of duty, justice and loyalty was strong. For light amusements she appeared to care little. She was a devoted member of her intimate family circle, unselfishly considerate in her friendships, steadfastly loyal to her principles, and deeply conscientious and sincere in her attachment to her religion and church. She bad the happy faculty of appreciating all that was worthy and lovable in others, and was possessed of a nature so full of sunshine that to her all of life became beautiful and full of meaning.

- Solon 1. Bailey, 1922

In the late 1800's, in a move considered bold and controversial at the time, Harvard Observatory began hiring women as "computers" to do tedious and time-consuming mathematical computations and examinations of photographic plates of stars. Conventional wisdom held that women had the patience to endure monotonous tasks that men would find too menial and boring; furthermore, women workers in all segments of society were paid far less than men. The women "computers" at Harvard Observatory were paid only one-fourth the wages that men were paid. Despite these inequities, however, the hiring of women at Harvard Observatory was extremely important, in that it first opened the doors for women to pursue careers as professional astronomers.

Conventional wisdom also held that only men had the intellectual capacity to engage in independent or theoretical research. Not surprisingly, however, a number of women "computers" (including Henrietta Leavitt) made many significant astronomical discoveries for which they generally received little recognition. Even the most talented female astronomers were hampered in their work by social prejudices and conventions, to say nothing of the jealousies and politicking of less-accomplished men. Indeed, Cecilia Payne-Gaposchkin, whose 1925 doctoral dissertation *Stellar Atmospheres* has been called "the most brilliant Ph.D. thesis ever written in astronomy," had this advice for young women thinking about a career in astronomy: *"Do not undertake a scientific career in quest of fame or money.... Undertake it only if nothing else will satisfy you, for nothing else is probably what you will receive. "*

Despite all odds and obstacles, more and more women have flourished in astronomy, in no small measure because of the efforts of earlier women astronomers who paved the way. Some, such as Dorrit Hoffleit, Senior Research Astronomer Emeritus at Yale University, and past Director of the Maria Mitchell Observatory (MMO) on Nantucket Island, made a special effort to mentor young women. While MMO Director, Hoffleit began a summer internship program for young women majoring in astronomy or related fields. More than 100 young women—affectionately referred to as "Dorrit's Girls"—participated in this unique program, and many of them have pursued notable careers in astronomy.

Caroline Furness, an important astronomer with a special interest in variable stars, also mentored many young women during her tenure as Director of Vassar Observatory. This same nurturing of women with an interest in astronomy continued with her successor, Maud Makemson. One of Makemson's students was Vera Rubin, who is currently one of America's most respected astronomers. Rubin discovered that the mass of a galaxy is not distributed in the same way that its light is-that, in fact, the vast majority of a galaxy's mass is concentrated away from its disc. This "missing mass" problem has had the astronomical community engaged ever since.

Rubin was the first woman to be granted official permission to observe at Mt. Palomar Observatory in California. The application sent to her from Mt. Palomar in 1964 included the printed statement, "Due to limited facilities, it is not possible to accept applications from women." At the time, there was only one bathroom at Mt. Palomar, labeled "Men." Fortunately, attitudes have changed (along with plumbing!) there and in many other parts of the scientific world.

In contrast to times past, contemporary women's dreams of becoming astronomers, astrophysicists, and astronauts seem entirely do-able, given enough desire, talent, and hard work. While much remains to be done to "open the heavens" for women and men in developing nations, thanks to the path-breaking achievements and nurturing efforts of Dorrit Hoffleit, Caroline Furness, Maud Makemson, and many others, astronomy is quite possibly the most "female friendly" of all the sciences.

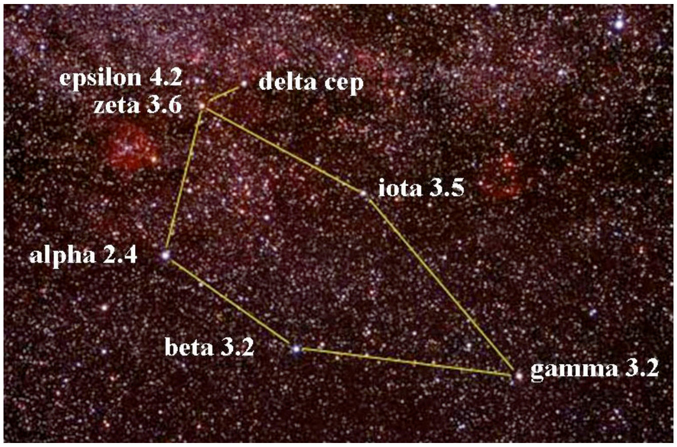
Activity 7.2: Observing the Variable Stars W Cygni and Chi Cygni

Now that you have practiced magnitude estimations with delta Cep—or if you are starting your variable star observations in the summer or early autumn—you may consider observing W Cyg. This is the variable star you used to learn how to estimate magnitudes in the previous chapter. The added familiarity makes this an ideal variable for you to observe.

Another interesting and dramatic variable star is chi Cyg. This is a red star with a large magnitude range. Both W Cyg and chi Cyg are located within the background clutter of the Milky Way and are not as easily visible as delta Cep.

If you have dark skies, you can observe chi Cyg with your unaided eye or binoculars only when it is at or near its maximum, which is magnitude 4.3. At other times, it is too faint to see without using a small to moderate-size telescope. In fact, chi Cyg drops to magnitude 14.1 at minimum!

SPACE TALK



Delta Cephei belongs to a class of variable stars called **pulsating variables**; in fact, delta Cep is the prototype for one type of pulsating variable known as **Cepheid variables.** Due to instability within their atmospheres, they continuously undergo rhythmic expansions and contractions, like a rock song with a definite beat. Some Cepheid variables have a quick rhythm, completing a cycle or period in a day; others take as many as 70 days. They are all giants or supergiants—delta Cep is a supergiant just over 1000 light-years away and 3300 times more luminous than our own Sun. Maximum brightness occurs near the time of greatest expansion, while minimum brightness coincides with the greatest contraction. There is evidence that not all the atmospheric layers are pulsating together; in other words, as the innermost layers have finished contracting and started expanding again, the outer layers are still contracting. When these layers meet they produce interior oscillations. The amazing fact is that in spite of all the bumping and grinding and colliding of different layers of chaotically expanding and contracting atmospheres, Cepheid variables pulsate with a period as regular as clockwork. Their periods are known to a fraction of a second, and the regularity of period hardly ever changes. The periods of only a few stars of this type change as much as 2 or 3 seconds within a 50-year period. When changes do occur, they usually happen smoothly. Sometimes, however, odd things happen. One strange case is that of RU Camelopardalis, which exhibited several sudden changes in periodicity, and then in 1965 stopped pulsating. Ever since, RU Cam has produced light at an apparently constant magnitude of 8.5. Except for these few eccentric relatives, however, most pulsating variables are locked into their own individual internal rhythms.

Another famous Cepheid variable is Polaris, the North Star! It is not surprising that its variation goes unnoticed, as it varies only from magnitude 2.5 to 2.6 with a four-day period.

In 1781, a 17-year-old Englishman by the name of John Goodricke began observing stars with his friends and neighbors, the Pigotts. Two years later, in 1783, the Royal Society of London presented him with the prestigious Godfrey Copley science medal.

Goodricke, deaf since birth, merited the honor through his patient observation and measurement of the star Algol's variability. Goodricke would later be credited with the discovery of an entirely new class of variable stars—the short period Cepheid variables, so named for the first star of its type discovered, delta Cephei.

Had Goodricke been born much earlier than 1764, he might never have had the chance to develop his talent for astronomy. Only a few years prior to his birth, most people equated deafness with idiocy, and did nothing to try to train or educate the deaf.

Fortunately, Goodricke's father had the means and knowledge necessary to find a place for John to be taught to read lips, speak, and to use an early method of sign language, along with the usual branches of learning available to well-to-do boys at the time.

The Cepheids are special in another way which makes them very important to a branch of astronomy known as **cosmology**—the study of the evolution of the universe. Cosmologists want to find the answers to such questions as: How did the universe begin? How will it end? What is the age of the universe? Cepheids can help answer that last question. In the early 1900's, Henrietta S. Leavitt discovered several faint Cepheids in the Small Magellanic Cloud (at the time thought to be a nebula within the Milky Way Galaxy). Henrietta calculated their light curves and determined their periods. She plotted an average brightness against the period and discovered that longer-period Cepheids are brighter than shorter-period ones. This led to the **period-luminosity relationship**, a plot of absolute magnitude versus period. In this form, Cepheids can be used at indicators of distance by applying the following steps:

1. Identify a star as a Cepheid variable by studying its spectrum (if possible) and/or by the shape of its light curve.
2. Calculate its period.
3. Use the period-luminosity relationship to determine the absolute magnitude.
4. Use the inverse-square law to calculate how far a star of that absolute magnitude would have to be moved from the standard distance of 32.6 light- years to appear as a star of the apparent magnitude observed.

Therefore, by finding a Cepheid variable and measuring its period and median apparent magnitude, one can determine its distance. When Edwin Hubble found 12 Cepheids in what was called the Andromeda nebula in 1923, and applied the period-luminosity relationship, he determined that Andromeda was so far away that it was not a nebula within the Milky Way but a galaxy in its own right. Hubble then devised his own relationship, called **Hubble's Law**, which states that the other galaxies in the universe are all moving away from the Milky Way—that in fact the universe is expanding. Hubble's Law states that the farther away a galaxy is, the faster it is moving away from us. Hubble's Law is written as follows:

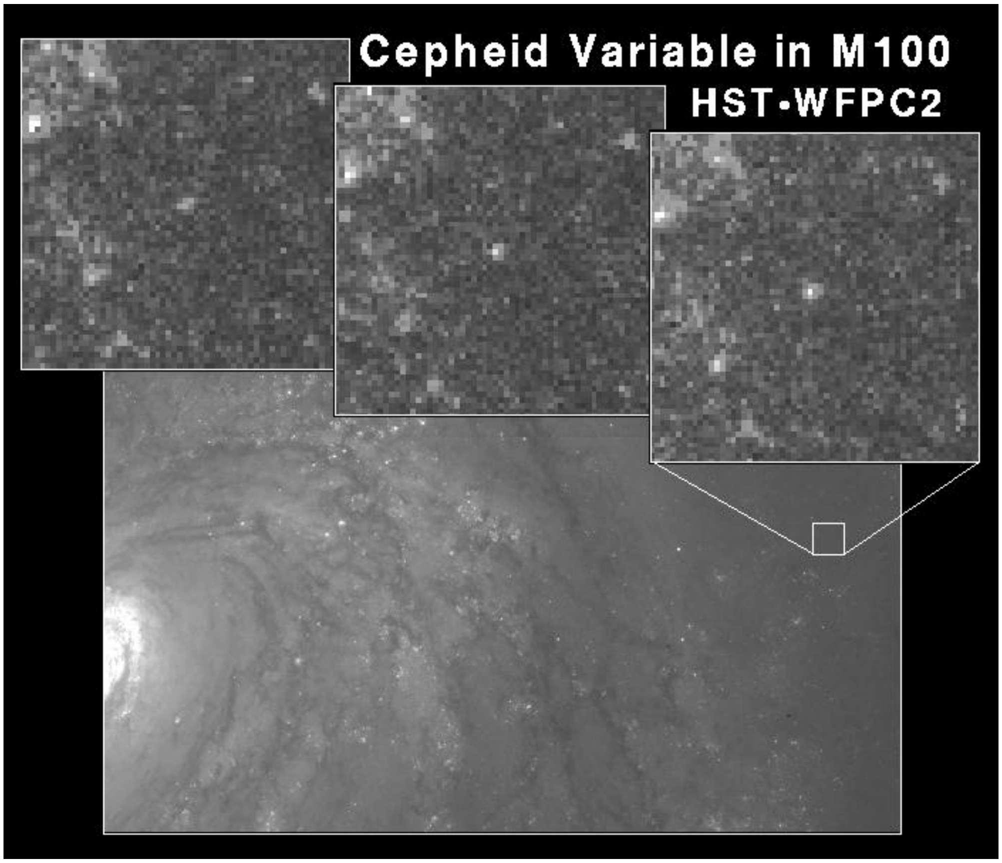
$$\boldsymbol{V_r = H_o d}$$

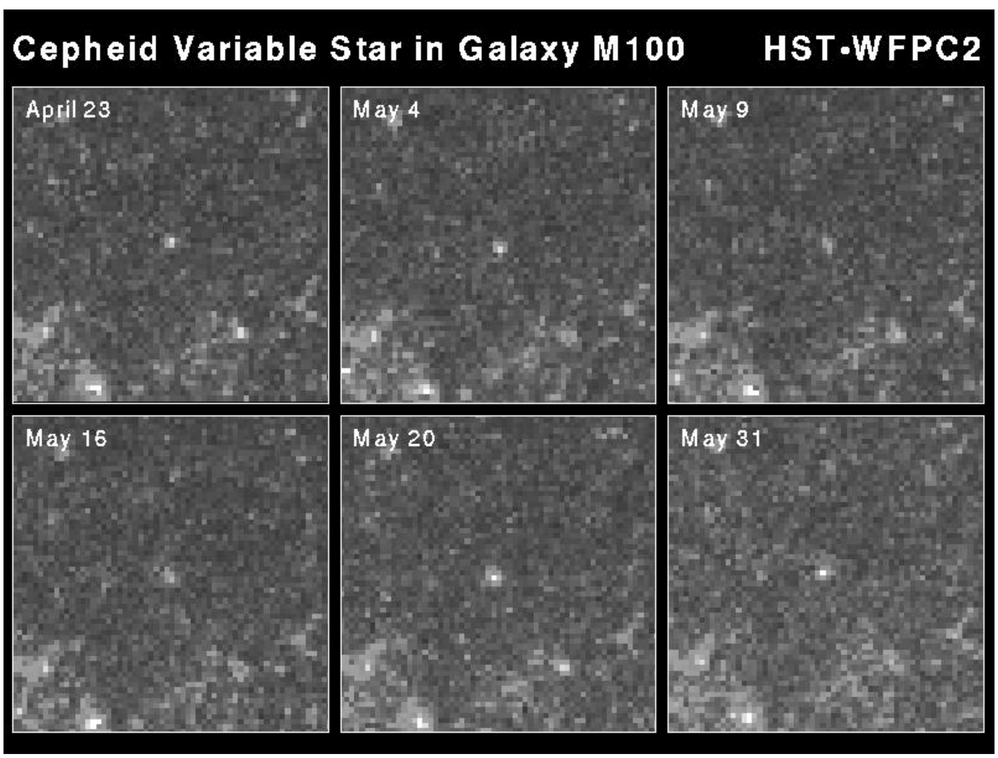
$\boldsymbol{V_r}$ = recessional velocity (how fast the galaxy is moving away from us)

$\boldsymbol{d}$ = distance (how far away the galaxy is from us)

$\boldsymbol{H_o}$ = Hubble's constant (the rate at which the velocity changes with distance)

Hubble's constant, then, is a measure of the rate at which the universe is expanding. The reciprocal of Hubble's constant is related to the age of the universe. The value of Hubble's constant depends upon knowing both the **recessional velocity** and the distance to faraway galaxies. The velocity can be measured by looking at the spectrum of a galaxy. One method of determining the distance to a galaxy is by finding a Cepheid in the galaxy and applying the period-luminosity relationship.


Cepheid Variable in M100
HST•WFPC2


Cepheid Variable Star in Galaxy M100
HST•WFPC2
April 23
May 4
May 9
May 16
May 20
May 31

Determining exactly how fast the universe is expanding is one of the most crucial unsolved problems in observational astronomy, fundamental to understanding the structure of the universe and verifying if the Big Bang theory is correct. It is so important that it is one of the high-priority missions of the Hubble Space Telescope (HST). To ascertain the value of Hubble's constant, the HST will measure the distances to Cepheid variables in 20 galaxies across the sky, as well as measure distances to Cepheids located in two galaxy clusters nearest to us centered in the constellations Virgo and Fornax.

HST has already proven that Cepheid variables can be found and tracked in galaxies more than 50 million light-years away. Using 20 Cepheids discovered by HST in M100—a spiral galaxy in the Virgo Cluster—a distance greater than 56 million light-years was measured. (See the two Hubble Space Telescope images on the preceeding page.) As the recessional velocity of the Virgo Cluster is approximately 1400 km/s, this yields a value of 80 for Hubble's constant. This value creates a serious problem, because the higher the value of Hubble's constant, the younger the age of the universe. The value of 80 implies an age of 8 billion years, in which case the universe would be younger than the objects it contains! However, the globular clusters which inhabit the galactic halo are thought to be 13 billion years old, which sets a lower limit on the age of the galaxy and therefore the universe. Of the several methods astronomers use to measure cosmological distances, ranges of 40–100 are obtained for the value of the Hubble constant.

So what is wrong here? First, the measurements HST determined using M100 may be wrong. After all, they are only one data set. Perhaps because of its huge mass and proximity to the Milky Way, it is gravitationally-bound in a way that gives a false value for its recessional velocity. Maybe M100 does not lie at the center of the Virgo Cluster as thought, but in front of or behind it. In this case, its recessional velocity would not be the same as the Cluster itself, since M100 has its own motions besides the motion of the whole Cluster. Is this a cosmological crisis of universal proportions? Will fundamental assumptions and theories survive? The universe is under no obligation to fulfill the expectations of current cosmological principles. This is an exciting time for astronomy. Our technology is becoming refined enough to test hitherto untestable theories—theories that have been in textbooks for decades. It will be interesting to see what happens!

There are other intrinsic variable stars besides Cepheids and other pulsating variables. There are several types of variables which undergo eruptions instead of pulsations. The most spectacular of these "eruptive variables" are supernovae, which are caused by catastrophic stellar explosions in massive dying stars. As stars die, heavier and heavier elements are produced by the fusion process. Eventually, in the most massive stars, the nuclear fires burn so hot that iron starts to fuse. All elements lighter than iron produce energy during fusion, but iron consumes energy. When iron starts to fuse, the stage is set for destruction—nothing can stop the complete and total collapse of the star. A star that has shone for millions of years ceases to exist in the visible universe in the cosmological blink of an eye, leaving behind beautiful layers of its atmosphere torn from its surface during its unimaginably violent death. Supernovae display light increases of 20 magnitudes or more and can outshine all other stars in a galaxy.

Another example of eruptive variables is novae. Novae result from stars in close binary systems in which each star is at a different evolutionary stage. For example, a star with its atmosphere bloated during the red giant stage may be orbiting a dense, hot white dwarf. The outer layers of atmosphere of the red giant whirl into a disk and spiral onto the surface of the white dwarf, causing nuclear explosions on the white dwarf's surface. The increase in brightness can range from 5 to 20 magnitudes.

While you perform your magnitude estimates in the backyard, take a moment to ponder this vast and ancient universe we inhabit. How ancient? How vast? Cepheid variables, just like the one you are studying, hold the key to unlocking the answers to these questions. Above you stars are exploding, literally tearing themselves apart with incredible violence. Others are locked into gravitational tugs-of-war as stellar atmospheres are stolen from red giants by their orbital companions, causing nuclear explosions to light up the sky. In the quiet solitude of backyard observing, remember that the stars above you are not eternal—stars are being born in the nuclear fires of stellar nurseries and dying when the fires begin to sputter and go out. As you progress with your quest to study the stars, the observations you make can help advance our understanding of the complex changes occurring overhead.

AM Herculis

One interesting example of a cataclysmic binary system variable star is AM Herculis. You can learn more about this unique system at http://www.aavso.org/vstar/vsots/0601.shtml

Chapter 7: Observing Variable Stars in the Real Sky

Summary

This chapter is the heart and soul of the *Hands-On Astrophysics* curriculum. Those instructors who have access to the real sky can make their students a part of the scientific process of variable star research. As long as your sky is not excessively bright, you will be able to systematically observe bright variables such as delta Cephei and W Cygni.

Terminology

AAVSO	GMAT	period-luminosity relationship
Cepheid variable	HIPPARCHOS	recessional velocity
cosmology	Hubble's constant	
finder charts	Hubble's law	

Common Misconceptions

1. *Stars do not change.*

2. *Only the data collected by professional astronomers are useful to science.*

3. *Telescopes are necessary to make serious measurements of the sky.*

SUGGESTIONS FOR THE POSTER PAGES, INVESTIGATIONS, AND ACTIVITIES
Poster Page: Starlight in Your Eyes

RESOURCE

Your students may be interested in determining their pupil size. An inexpensive pupil gauge can be obtained from the ***Sky Publishing Corporation***. (See Resource List.) Research on diseases of the eye, and how they change vision and affect skywatching, is an area full of possibilities for discussion. Have the types of vision problems changed over time? Did ancient peoples have different diseases and problems? What did they do about visual deficiencies? When were glasses developed? How well did they work? When were filters first used? Were they effective? When was glass developed, and how was it used when first discovered? Does radiation affect eyesight? If so, what precautions should be taken? Did any famous astronomers have vision problems? How do we know this? What about seeing colors and color blindness? The human eye has three types of color cones. Blue, green, and red cones respond to light across the visible spectrum. Their coverage overlaps quite a bit. The green cones, for instance, respond somewhat to red and blue light.

Every color in the spectrum produces a different ratio of red, green, and blue response in the eye. The brain interprets each mix of responses as a different color. How are "true" colors affected by atmospheric conditions? Does aging seriously change the reliability of amateur variable star observers? (In other words, do younger observers see the stars better than older observers?) Can this aging factor be detected and accounted for? Can it be considered a systematic error?

Poster Page: Occupational Hazards of Variable Star Observing

Sometimes funny things happen to amateur variable star observers! If you have internet access, you can find the complete archive of messages for the AAVSO's on-line discussion group. The address is

http://mailman.mcmaster.ca/mailman/listinfo/aavso-discussion

Core Activity 7.1: Observing Your First Variable Star—Delta Cephei

Delta Cephei is recommended as a first observational activity for several reasons. It is circumpolar in the Northern Hemisphere. It is visible from most northern latitudes, at least for a large portion of the year. It is outside the distracting clutter of the Milky Way stars and in a relatively dark part of the sky. Its comparison stars are close by and have magnitudes which approximate the range of delta Cephei. The star is bright enough for unaided eye observation, even at minimum. Also, its period is short enough that a month's observations will yield excellent results.

The student pages do not reveal the range in magnitude or the period. This information is to be given out at your discretion, depending on your group of students. The period for delta Cephei is 5.36 days, and it ranges from a maximum magnitude of 3.5 to a minimum magnitude of 4.3. The students will need the finder charts and the Julian Day numbers provided in this manual, as well as their planispheres, and if available, a *Sky Gazer's Almanac.*

Depending upon your location and the time of year, you may choose one of the other recommended variable stars listed below for which the AAVSO has provided slides and a set of finder charts. They make good independent study or science fair projects as well as long-term class projects.

R and RT Aur
Chi, W, X, and U Cyg
R, S, and Z UMa
T, S, and U Cep
R and V Cas

Students are given the tools to convert their time and date of observation to the Julian Date (JD). Depending on your students, you may elect to have them perform the calculations, or simply use the Julian Day without converting their observation time into the fraction of the day. This would suffice for the classroom. If some of your students would like to have their observations added to the American Association of Variable Star Observers International Database, however, the complete JD will have to be calculated.

Depending upon your location, or because it will add more validity to the observational data, you may decide to involve another group of students in observing delta Cephei. Then your students can compare their data with others. Compiling all the data will further reduce random error, or perhaps bring to light a previously undetected systematic error. An additional advantage of having data from another class is that they may be able to fill in gaps in your data. For example, you may lose several viewing days due to adverse weather conditions at your site that the other class may not. If you have an internet connection, students could exchange information on a regular basis, or they could correspond by fax or regular mail.

Observing with Binoculars

Delta Cephei can be seen with the unaided eye if you have dark skies, and binoculars are not necessary. Some of the variables on the list *will* require binoculars. Binoculars are extremely underutilized astronomical tools. Most people have the impression that telescopes are necessary to view objects in the sky, and do not consider binoculars—even though many people own a pair. There is no reason or need to purchase a telescope if a pair of 7x35 or 7x50 binoculars is available. They are portable and require no setup time. Binoculars have wide fields of view that are oriented right side up, making it much easier to find celestial objects than with a telescope (which gives an inverted image). In fact, there are a large number of objects for which binoculars provide *better* views than popular telescopes. This is because telescopes have a very small field of view and many objects do not "fit" in the scope. The Pleiades, Hyades, Milky Way star clouds, Rosette and North American nebulae, and the face-on spirals M33 in Triangulum and M101 in Ursa Major are examples. 7x35 binoculars are sufficient; however, the best binoculars for astronomical use are the 10x50 wide angle instruments. Larger binoculars are expensive and so heavy that a tripod is required.

Poster Page: She Discovered How to Calculate the Distances to Galaxies (Henrietta Leavitt)

Women have always made significant contributions to astronomy, including variable star astronomy. History is filled with brilliant women astronomers who worked as assistants to husbands, family members, or professors and made many discoveries for which they received little or no credit. With the advent of the application of photography to astronomy, thousands of star fields, spectra, and charts needed to be examined. During this time (the 1880's) women were hired as "computers." It was believed that men would be too bored with the incredible amount of routine work and tedious calculations that such examination required. Women were not only patient, they were also cheap labor. They were allowed the drudgery of cataloging, recording, and classifying. Independent research and theoretical work was attended to by men, since women were thought to be incapable of higher levels of thinking. The women who became accomplished astronomers did so under adverse circumstances and few received recognition.

Some famous women astronomers are listed below. Their lives make interesting research topics. There are still many disadvantages for women in any field of science, including astronomy. How much has changed in the past 200 years? Has the percentage of women astronomers increased? Decreased? Is it different from other fields? Find a woman astronomer to interview (there are many besides the pioneers listed below).

You may elect to compare the status of women astronomers and scientists with that of women in other countries. In which cultures is it easier for women to enter scientific fields?

PAST ASTRONOMERS

Catherina Elizabetha Hevelius (1646–1693)
Wife and assistant to the Polish astronomer Johannes Hevelius. After his death she published two catalogues, one of which contained 1,564 stars. This was the last and largest star catalogue compiled without a telescope.

Nicole-Reine Lepaute (1723–1788)
An extraordinary mathematician who worked with the French astronomers Clairaut and Lalande to predict the path of Halley's Comet, successfully predicting its 1757 return. She also predicted the annular eclipse of 1764.

Caroline Lucretia Herschel (1750–1848)
Assistant to her brother, William Herschel, who discovered Uranus. She discovered 8 comets, and reduced and published William's observational data on nebulae.

Maria Mitchell (1818–1889)
First woman astronomer and first professor of astronomy in America. She discovered a comet in 1847, for which she received a gold medal from the King of Denmark. She became the Director of Vassar College Observatory in 1865.

Williamina P. Fleming (1857–1911)
Discovered over 300 variable stars and 10 novae (one of which was later identified as a supernova) by looking at their spectra.

Winnifred Edgerton (1862–1951)
The first American woman to receive a Ph.D. in astronomy. Her husband insisted that she give up her career and stay home to fulfill her family responsibilities.

Annie Jump Cannon (1863–1941)
Classified the spectra of many thousands of stars, using the stellar classification system (OBAFGKM) of decreasing stellar surface temperature, which utilizes the strength of all spectral lines.

Dorrit Hoffleit (1907–2007)
Spent the first half of her astronomy career at Harvard, and second half at Yale, until she retired as Senior Research Astronomer Emeritus. Made a pioneering study of the light curves of meteor trails, and discovered 1270 variable stars.

Antonia C. Maury (1866–1952)
Developed her own classification system for stars; although awkward to use, it led to the recognition of luminosity classes and the existence of giant stars.

Henrietta Swan Leavitt (1868–1921)
Discovered the period-luminosity relationship in Cepheid variable stars, which led to Cepheids being used to measure distances to other galaxies.

Cecilia Payne-Gaposchkin (1900–1979)
Her doctoral thesis, *Stellar Atmospheres*, has been called the most brilliant Ph.D. thesis ever written in astronomy. She determined that stars were composed mostly of hydrogen and helium.

Henrietta Hill Swope (1902–1980)
Discovered 2000 variable stars and used variables on photographic plates to establish the distance to the Andromeda Galaxy.

SOME CURRENT ASTRONOMERS

Vera Rubin
She was the first woman to have official permission to use the Mount Palomar telescopes. Her work established the presence of "dark matter" in the universe.

Jocelyn Bell Burnell
She was the Chair of the Department of Physics at the Open University in Great Britain. Discovered pulsars in the late 1960's.

Lucy McFadden
A recognized authority on the nature and interrelationships of asteroids, meteorites, and comets.

Carolyn Porco
The head of the Voyager team that studied planetary rings and discovered the faint rings of Neptune.

Margaret Geller
Responsible for the discovery of the large-scale structure of the universe, and that galaxies are clustered around the edges of great voids shaped like bubbles.

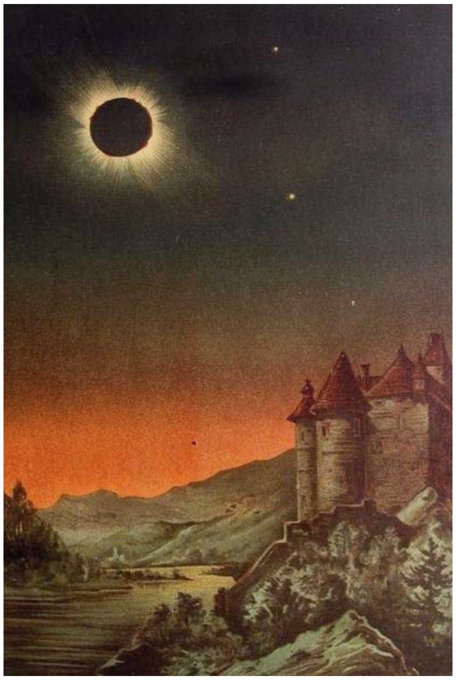
Sandra Faber
Determined the existence of the "Great Attractor" 150 million light years away in the direction of Centaurus, a huge mass pulling neighboring galaxies toward it, including the Milky Way.

Heidi Hammel
Principal Research Scientist at Massachusetts Institute of Technology. Team leader for the Hubble Space Telescope imaging of Jupiter during the impact of Comet Shoemaker-Levy.

Activity 7.2: Observing the Variable Stars W Cyg and Chi Cyg

W Cygni is the variable star used in the slide set which taught students how to estimate magnitude variation. It would therefore be an excellent follow-up project after delta Cep. It could also be used as a first project. W Cyg and chi Cyg are not listed first in this chapter because Cygnus is part of the Summer Triangle, and if you do not get to this part of the curriculum before early autumn, Cygnus leaves the sky. These stars are ideal variables for observing from late spring through summer, and even into early fall if the horizon is unobstructed. However, chi Cyg is only visible (with the unaided eye or with binoculars) when it is near maximum; if it is closer to minimum you will need a small to moderate-size telescope. Furthermore, both chi Cyg and W Cyg are embedded within the background clutter of Milky Way stars, and so it may take some practice to locate them against this starry background. Students can practice locating these stars with the provided slides.

Chapter 8: The Nature of Light



Introduction

One can only imagine the terror experienced by ancient skywatchers during solar and lunar eclipses. Eclipses were regarded by many cultures as the death of the Sun; both solar and lunar eclipses were thought to be caused by monsters or wild animals attacking and devouring the Sun or Moon. Eclipses were also associated with the outbreak of epidemics and plagues.

To watch darkness descend over the world in the middle of the day was regarded by all ancient cultures as a sign of cosmic disorder. Angry gods and monsters were threatening to destroy light and plunge the world into eternal darkness. The Mayans especially feared solar eclipses, considering them to be the violent triumph of night beings over the day. To Mayans, form-changers demons prowled the night, and supernatural beings tried to communicate with mortals. Even late into the 1600's, people were fearful of eclipses, hiding in cellars, and covering their wells to prevent sky poisons from dripping into their drinking water.

Eclipses are fascinating to watch. It truly is an uncanny experience to see midday turn into a night dotted with stars. One astronomer from the 19th century, in describing an eclipse, stated: *"A profound calm reigned in the air; the birds sang no more."*

Eventually, skywatchers understood that lunar eclipses were the result of the Moon moving into the Earth's shadow, and that solar eclipses occurred when the Earth moved through the Moon's shadow. Thales of Miletus, a philosopher, made the first known prediction for a total solar eclipse in 585 BC. Thales only had the knowledge to predict the year, not the month or day of the eclipse.

The Anasazi Indians of Chaco Canyon had many solar observatory stations. In the harsh climate of the desert, where living conditions were marginal at best, the annual journey of the Sun was important for survival. In 1096 and 1097, total solar eclipses were observed in the American Southwest and recorded in painted rock art and designs chiseled into stone. The dependence on the Sun and its religious importance to the Anasazi induced them to become knowledgeable solar skywatchers.

Battle between the Lydians and Medes halted by the total eclipse of the Sun, May 28, 585 BC

However, it is now known to have occurred on May 28th. It is the first historical event dated to the day by computing times of previous eclipse events. At the time, a lengthy war was taking place between the Lydians and the Medes, and a battle was in progress on the day the eclipse occurred. The abrupt transformation of day into night shocked the two sides into ceasing their fighting. They immediately formulated a peace treaty involving two marriages between the opposing sides. Neither side knew about Thales' prediction.

Humankind has had a long and convoluted journey towards understanding the true nature of light. A common belief of the Greeks was that the eyes were the source of light, and therefore illuminated objects that their gaze fell upon. Plato maintained that the sensation of sight was caused by the union of three beams. The first was a stream of divine fire" emanating from the eye itself; the second, light issuing from the seen object; and third, the radiance from the Sun. Plato looked upon these beams as something like tentacles blindly seeking one another, until they came into contact and united. Others thought that light was an invisible fluid present at all times and in all places, but which had to be somehow ignited to be seen.

Isaac Newton hypothesized that light consisted of vast quantities of invisible particles thrown off from a luminous source. Ten years later Christian Huygens, a Dutch physicist, formulated the first clear statement of the wave theory—that light consisted of waves emanating from a luminous surface. But because Huygens could not explain all observable behaviors of light with his theory, and because Newton's authority as a scientist was so great, Newton's corpuscular theory of light was widely accepted. Unfortunately, this retarded the development of the wave theory for the next one hundred years. Proponents of both the particle and wave theories believed that light required a medium through which it would travel, and since light travels across space in which there is no matter, then the whole of space must be filled with this medium, called "ether." Huygens conceived of the ether as an elastic solid through which the waves were transmitted from the luminous source. We now know that "ether" is not necessary: light requires no medium through which to travel. Both Huygens and Newton were partially correct about the nature of light—light exhibits the characteristics of waves when traveling, and the characteristics of particles when interacting with a surface—and the *wave-particle duality* of light is now commonly accepted.

The effort to understand light has been accompanied by the desire to control it, as people strove to extend daylight by illuminating the night. At the end of the 1700's, life was still regulated by the hours of daylight, and tallow candles were the primary means of providing limited visibility at night. Wax candles were made from honeycombs and bayberries. During this time it was discovered that whale oil was more efficient than candles, and whale oil lamps provided street lighting in large cities. The demand for whale oil was so great that whales were hunted to near extinction.

The invention of each successive light source, from candles to whale oil to kerosene and gas, was a refinement of the previous method, but resulted in a greater danger of fire, explosions, and asphyxiation. It was not until after the nature of light was finally understood that the development of Edison's safe and efficient electric light was possible. An explanation was provided in 1873, when James Clerk Maxwell presented his equations dealing with electromagnetic theory. Maxwell, through his mathematical equations, was the first person to understand that visible light was just one of the many wavelengths of electromagnetic radiation.

Our understanding of light has changed dramatically since natural philosophers in ancient Greece first studied and speculated about its nature. Since we see the universe as light traveling through spacetime, we will now focus on its wavelike nature.

Investigation 8.1: The "Flavors" of Light

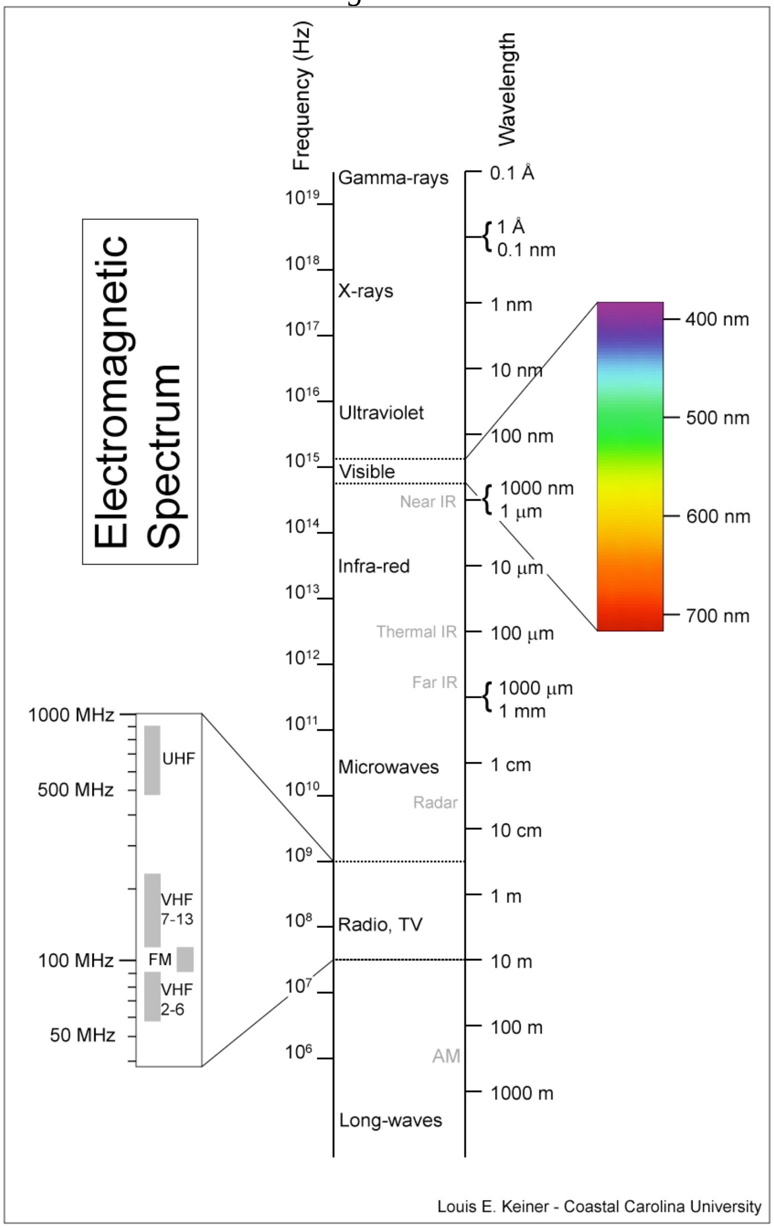
You will be given a set of objects by your instructor. Using these objects, investigate the light sources around you. Make a list of characteristics that these objects help reveal about light. Discuss your observations with the rest of the class.

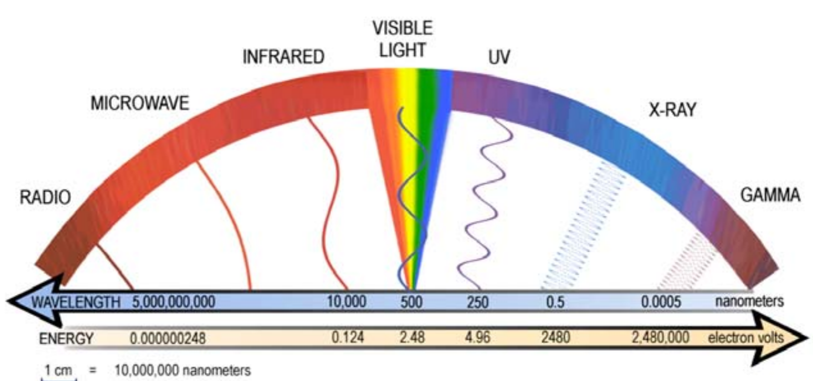
The Electromagnetic Spectrum

Visible light, when separated into its individual parts, exhibits a rainbow or *continuous spectrum* of colors. Each color is associated with a different *wavelength*. These wavelengths of light continue on either side of the visible spectrum beyond our abilities to detect them visually, but we can "see" them by using specialized instruments. All of these wavelengths together form the *electromagnetic spectrum*, and are also referred to as *electromagnetic radiation* (EMR).

According to the wave model of electromagnetic radiation, the different parts of the electromagnetic spectrum differ from each other only by their wavelengths. The wavelengths of EMR sources differ (going from longer to shorter) as follows: radio, microwave, infrared, visible (red, orange, yellow, green, blue, violet), ultraviolet, x-ray, and gamma ray. Non-visible wavelengths are not called "colors" but are referred to as "bands" of radiation; for example, the *microwave band* (see Figure 8.1 on the next page).

Figure 8.1


Electromagnetic Spectrum
Frequency (Hz)
Wavelength
Gamma-rays
0.1 Å
10^{19}
1 Å
0.1 nm
10^{18}
X-rays
1 nm
10^{17}
10 nm
10^{16}
Ultraviolet
100 nm
10^{15}
Visible
Near IR
1000 nm
1 µm
10^{14}
Infra-red
10 µm
10^{13}
Thermal IR
100 µm
10^{12}
Far IR
1000 µm
1 mm
10^{11}
Microwaves
1 cm
10^{10}
Radar
10 cm
10^{9}
1 m
10^{8}
Radio, TV
10 m
10^{7}
100 m
10^{6}
AM
1000 m
Long-waves
400 nm
500 nm
600 nm
700 nm
1000 MHz
UHF
500 MHz
VHF
7-13
100 MHz
FM
VHF
2-6
50 MHz
Louis E. Keiner - Coastal Carolina University


VISIBLE
LIGHT
INFRARED
UV
MICROWAVE
X-RAY
RADIO
GAMMA
WAVELENGTH 5,000,000,000 10,000 500 250 0.5 0.0005 nanometers
ENERGY 0.000000248 0.124 2.48 4.96 2480 2,480,000 electron volts
1 cm = 10,000,000 nanometers

A band of radiation is defined by its *wavelength*. One wavelength is the distance between adjacent troughs or crests (see Figure 8.2 below).

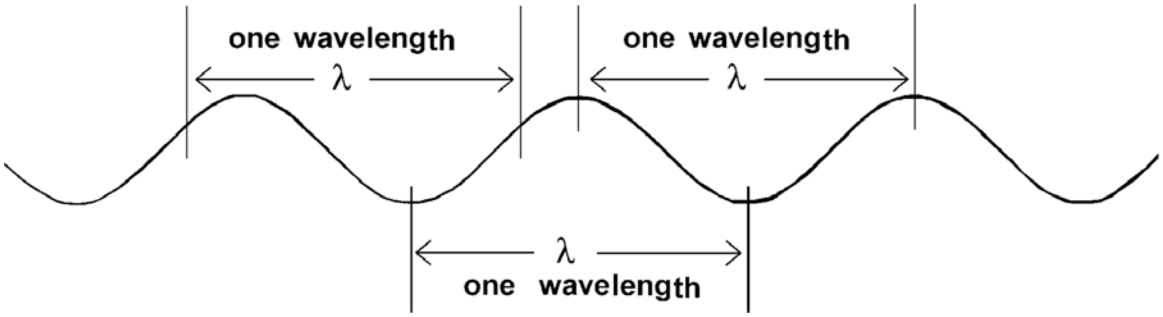


Figure 8.2

All EMR travels at the speed of light, 3 x 10^8 m/s, when traveling through space. In addition to wavelength (λ) and speed (c), another important property of waves is their frequency (*f*). This is a measure of how many waves pass a given point in one second. In other words, frequency is the number of cycles that occur in one second. The shorter the wavelength, the more that can occur in one second, and thus the higher the frequency. The longer the wavelength, the fewer that can occur in one second, and thus the lower the frequency. Frequency is measured in cycles per second (cps) or Hertz (Hz). Since all wavelengths travel at the speed of light, the relationship among speed *c* (the abbreviation for *celerity*), frequency (*f*), and wavelength (λ), can be stated as follows:

$$c = f \lambda$$

The different bands of EMR consist of little packets of energy—called *photons*—traveling through space. The amount of energy (*E*) they possess is directly related to their frequency (*f*). Radio photons have a low frequency and correspondingly low energy; gamma ray photons have the highest frequency and therefore the highest energy. This simple relationship can also be stated mathematically:

$$E = hf \, ,$$

where *h* is a universal constant called Planck's constant and equals 6.626 x 10^{-34} Joule-sec. (The metric unit for energy is the Joule (J), and 3.6 x 10^6 J is equivalent to 1 kilowatt-hour, or kw-hr.)

"Seeing" the Electromagnetic Spectrum

As the visible band of EMR strikes our eyes, it is focused by the lens onto the retina in the back of the eye. The rods and cones in the retina then stimulate nerve impulses which travel to the cerebrum, which converts this information into an image. We do not have the ability to convert any of the other bands of EMR into a visual image; we must use suitable sensors to capture radio, microwave, IR, UV, X-ray, and gamma ray wavelengths. Another barrier to our detecting nonvisual bands of radiation from outer space is the Earth's atmosphere. The atmosphere is opaque to most forms of radiation—except for small "windows" where those parts of the spectrum can penetrate to the surface of the Earth (see Figure 8.1). Balloons, rockets, and satellites are launched carrying telescopes and other instruments to detect other bands of radiation such as UV and IR. Even optical telescopes such as the Hubble Space Telescope (HST) are launched into orbit to avoid atmospheric conditions which interfere with the "seeing" of radiation from celestial objects.

The visible light we *can* detect from stars and other celestial objects gives us much more information than a simple image. One of the most powerful tools available to astronomers is the *spectroscope*, a device through which light is passed to produce the *spectrum*. Sometimes it is recorded on a photographic plate. The analysis of the spectrum from a star tells astronomers its mass, age, composition, motions, temperature, and evolutionary history. The study of the analysis of spectra is called *spectroscopy*.

The most common type of spectrum is the *continuous spectrum*, which we commonly refer to as the "rainbow." As you would observe outdoors, there are no parts of a rainbow that are either very dark or very bright compared to the rest of it. Likewise, there are no dark lines that stand out in the continuous spectrum where any wavelengths of color are missing (*absorption lines*); and there are no bright lines that stand out in the continuous spectrum where certain wavelengths of color are being produced (*emission lines*). If neither emission nor absorption lines appear, then the light source is glowing in all colors equally and is said to be giving off "white light." A common example of such a source of white or continuous light is an incandescent light bulb.

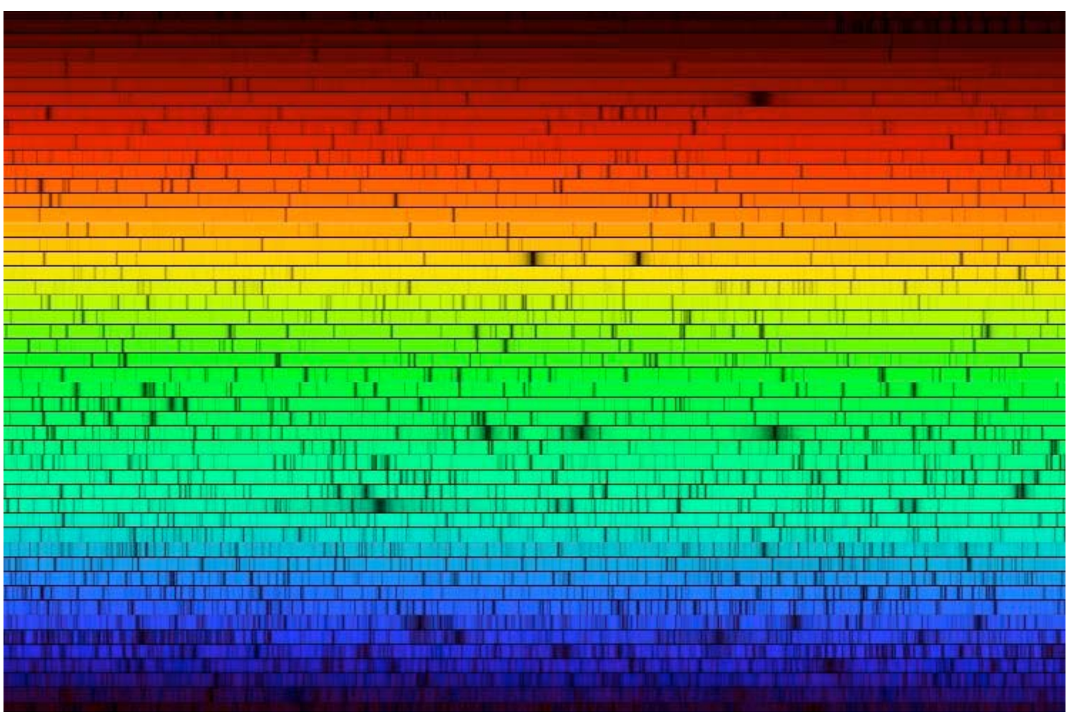
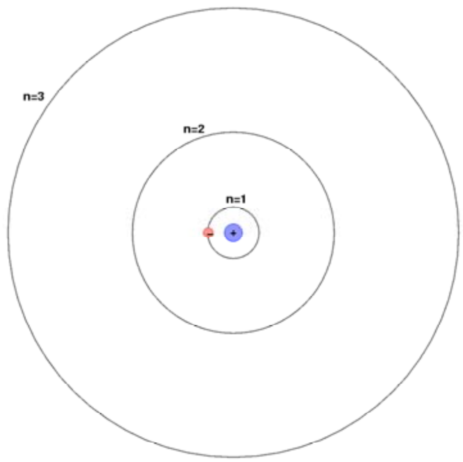
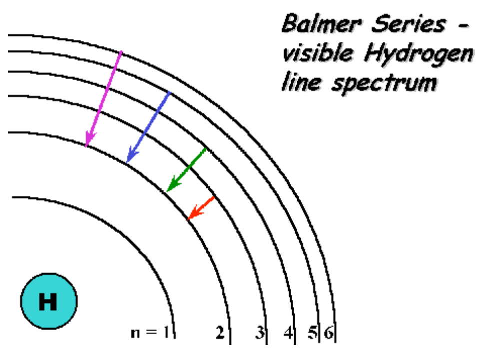


Figure 8.3 – Optical Solar Spectrum with Absorption Lines, Kitt Peak



Bohr Model of the hydrogen atom



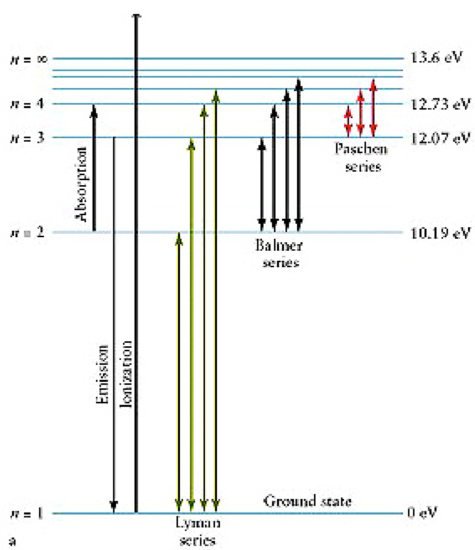


Figure 8.4 –
Four views of the hydrogen atom

If a single source, such as hydrogen gas, is heated or otherwise excited to luminescence, and this light is passed through a spectroscope, you would see that only certain colors or spectral lines are produced instead of a continuous band of colors. This is called an emission or bright line spectrum (see above). The reason for the presence of emission lines can be understood by looking at the atomic structure of the hydrogen atom. The Bohr model (at left) is a greatly simplified schematic representation of the hydrogen atom.

The next two accompanying energy level diagrams are different representations of the Bohr hydrogen atom model.

The single electron of the hydrogen atom can exist at different energy states (levels) or orbits around the nucleus. Each of these levels corresponds to a specific amount of energy, and no electron may occupy the spaces between these levels or orbits. In the diagram, the electron is in the first energy level, referred to as the *ground state*. Five other "allowed" states are represented. As the hydrogen atoms within the hydrogen gas are heated, collisions take place between electrons, and some of the electrons become "excited" by absorbing energy from these collisions. Some electrons will absorb the exact amount of energy necessary to "jump" to a higher energy state. The electron(s) will then spontaneously drop back down to a lower energy level, releasing their excess energy as electromagnetic radiation in the form of *photons*. The energy of the photons is equal to the difference in energy between the two energy levels, and is associated with a specific wavelength and frequency. The electron does not have to fall back to ground state all at once and give off one wavelength of radiation; it can fall back in "steps" from one energy level to another on its way back down. Every time it lands on an energy level, it gives up a wavelength equal to difference between the two energy levels. If the electron gets “bumped” up to energy level 4, it can drop down in any of the following ways: 4 to 1 *or* 4 to 3 to 2 to 1 *or* 4 to 3 to 1 *or* 4 to 2 to 1. (See Figure 8.4.) Electrons dropping back down to energy level 1, or ground state (the *Lyman series*), produce wavelengths in the UV part of the spectrum and are not visible. Those dropping back down to the second energy state are referred to as the *Balmer series* and result in wavelengths in the visible part of the infrared (or IR) band.

Because every element has a different number of protons in the nucleus, the first “allowed” energy level where the electrons can orbit is at a different distance for every single element. The distance from the nucleus of all the remaining orbital levels or energy states for electrons depends on the first orbital level or energy state. Since the distances are different between energy states (orbital levels) for all elements, the wavelengths of radiation produced by electrons falling down from one energy level to another energy level are different. Therefore, compared to other elements, the distance between any two energy states or orbital levels for *every single element is unique.* Since the energy is different, the wavelengths of radiation produced are different. Therefore the emission lines produced by every single element are unique to that element, like your fingerprints are unique to you.

In 1868, during an eclipse of the Sun, the French astronomer P. J. C. Jansen saw a bright line in the yellow part of the Sun’s spectrum, coming from a prominence on the Sun’s limb. The line was different from any previously-observed spectral line. It was also seen by the English astronomer Sir Norman Lockyer, who concluded that it originated in a gas as yet unknown on Earth. He named the unknown element “helium,” after “helios,” the Greek word for the Sun. It wasn’t until 27 years later, in 1895, that Sir William Ramsay found a laboratory gas which produced the same bright line in the yellow part of the spectrum. Helium is the second most abundant element in the stars; however, it occurs rarely on Earth, and so was originally discovered through analysis of the Sun’s spectral lines.

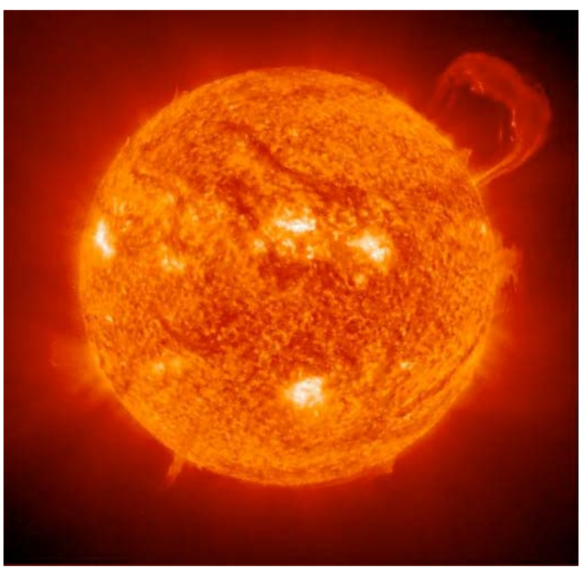


Figure 8.5 - A solar prominence captured on September 14, 1999.

Core Activity 8.2: Spectra of the Elements

To access a set of activities, materials, and resources about the electromagnetic spectrum: *Modeling the Spectrum* at http://chandra.harvard.edu/edu/formal/ems/

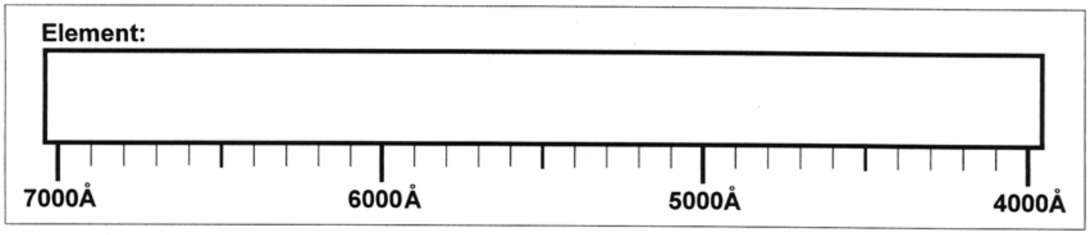
A. You will be provided with a spectroscope. Light enters the spectroscope through a narrow slit and becomes separated into its component colors. Look at the light from an incandescent light source with the spectroscope and you will see the full spectrum of colors. Notice there is a scale inside the spectroscope for the wavelength range of visible light. The scale is either in nanometers or angstroms (400 nm = 4000Å). You will be provided with several spectrum tubes that contain elemental gases. For each element, draw in the emission lines in color at the appropriate wavelengths which you see on the blank spectra sheet provided. Use the same colors you see, and record the names for the elements.

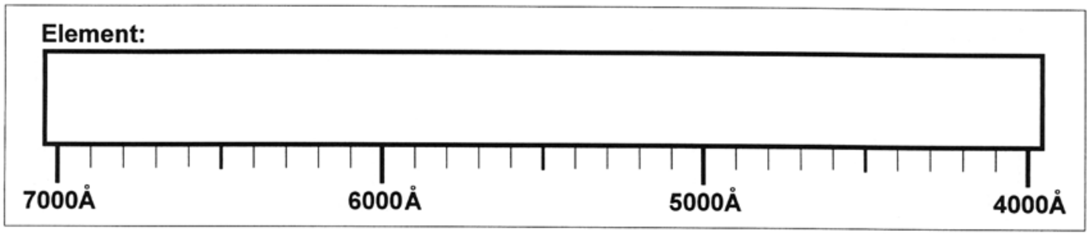
   Study the spectra that you have recorded. Are the emission lines different for each element?

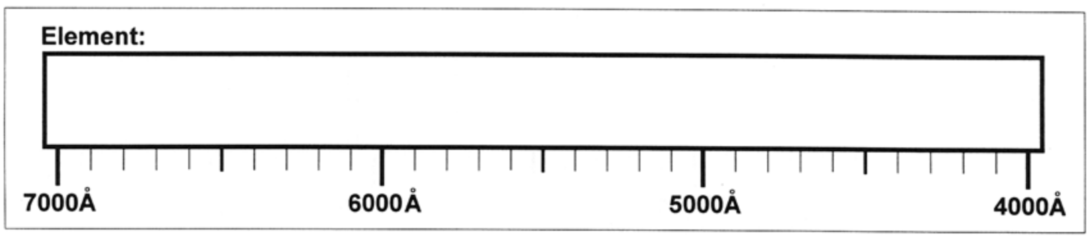
B. Study the spectra of the elemental gases given in the following pages. Some characteristic emission lines have been represented. If you have observed some of these elements already, you may notice that the emission lines you have recorded differ from the ones represented on the following pages. Your spectroscope is precise enough to show only the most dominant lines. Most elements have many lines, and the most dominant lines may not have been selected. Two mixtures have also been included.

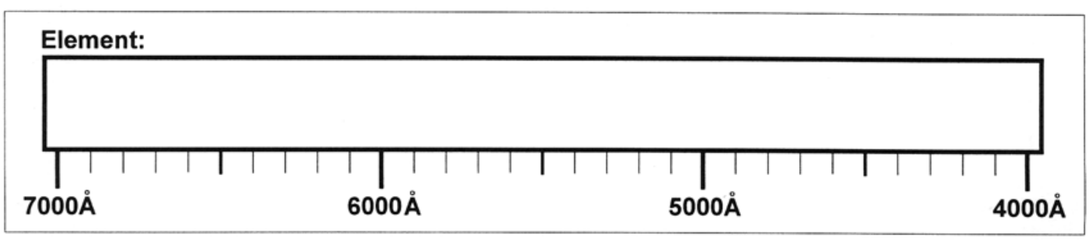
C. Since the emission lines of elements are unique, their spectra can be identified when there are several elements mixed together. Five unknown mixtures of the elements above are represented. Identify which of the elements in part B are in the unknown spectra (numbered 1–5) in part C on the pages following.

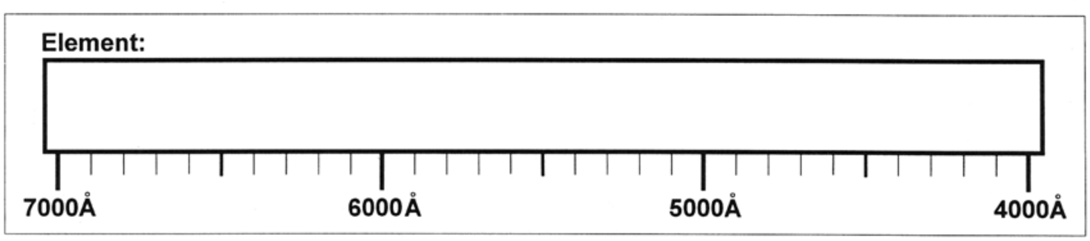
A. Blank Spectra





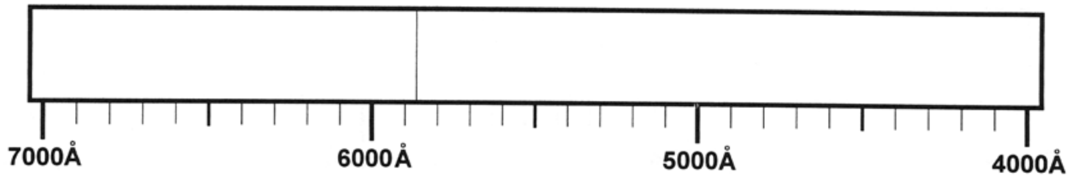




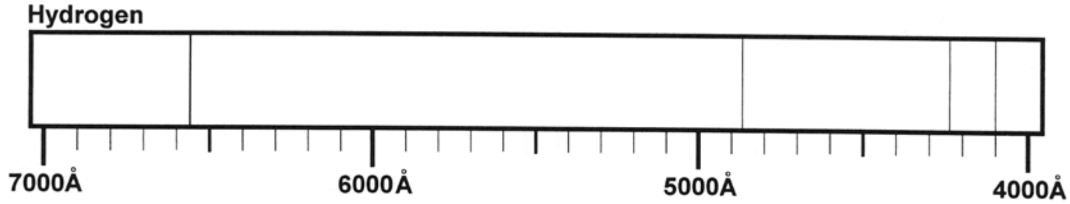


B. IDENTIFIED SPECTRA, PAGE 1

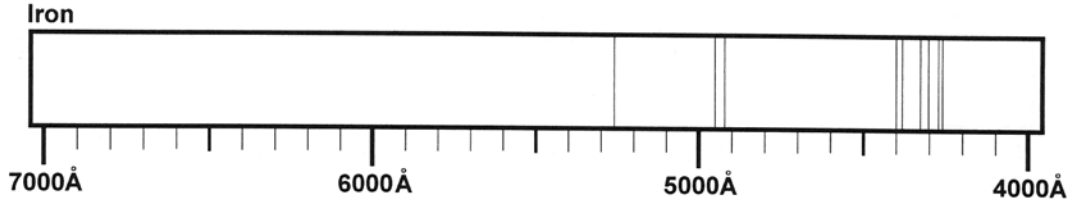
Helium



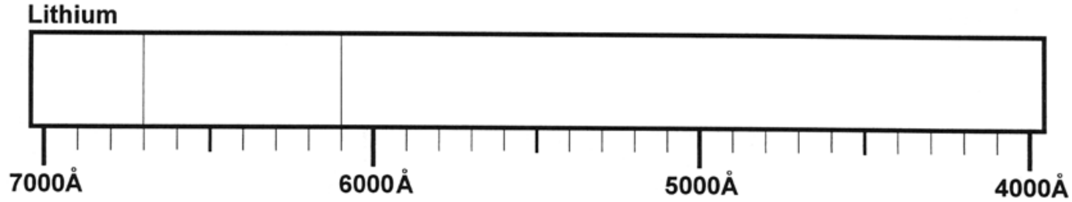
Hydrogen



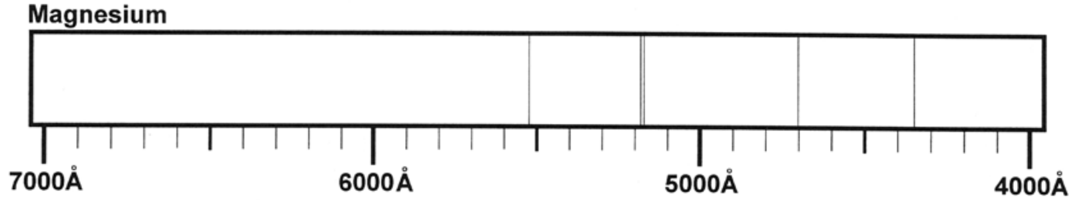
Iron



Lithium

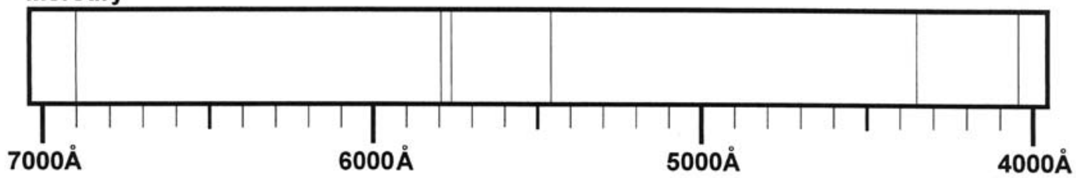


Magnesium



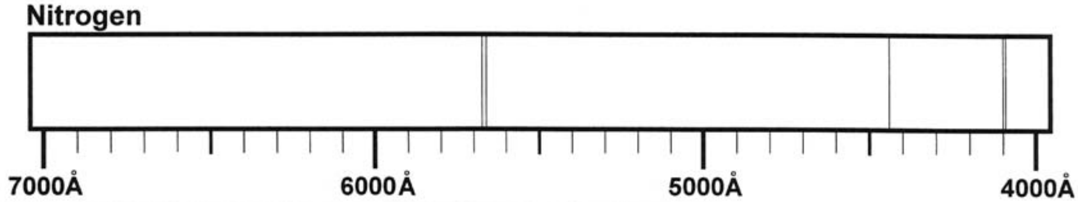
B. Identified Spectra, page 2

Mercury

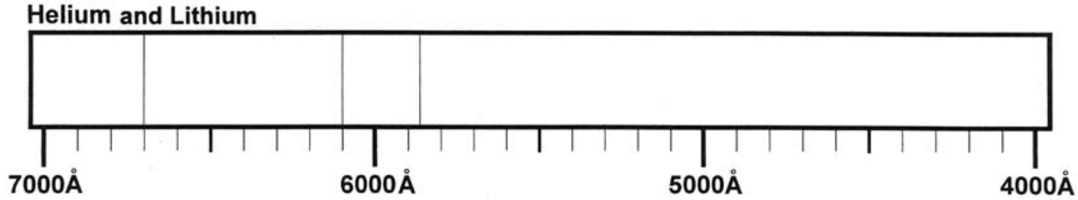


Neon

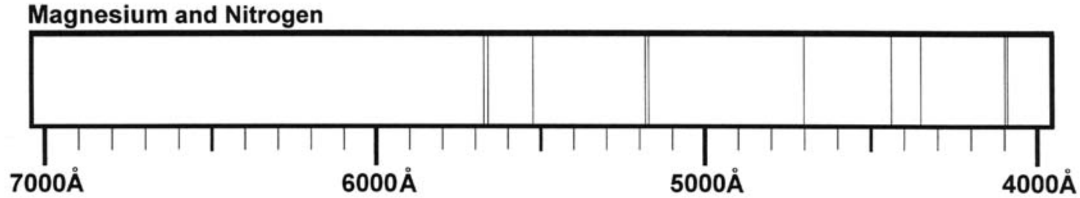
Nitrogen



Helium and Lithium

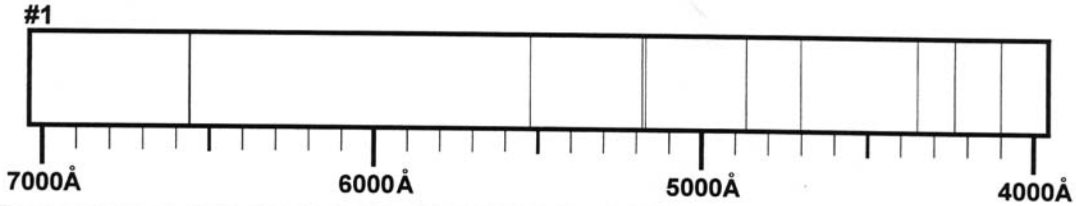


Magnesium and Nitrogen

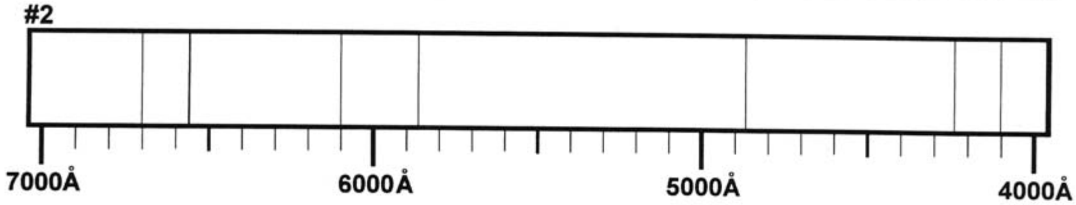


C. Unidentified Spectra

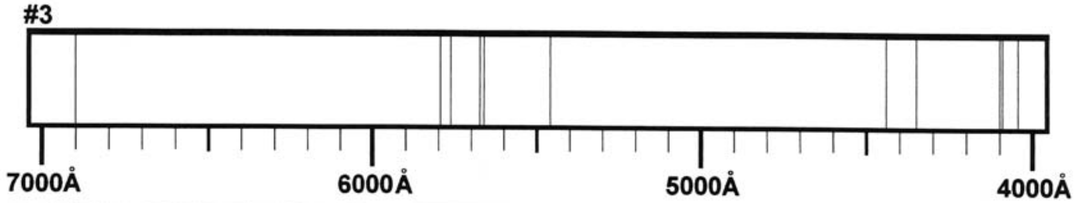
#1



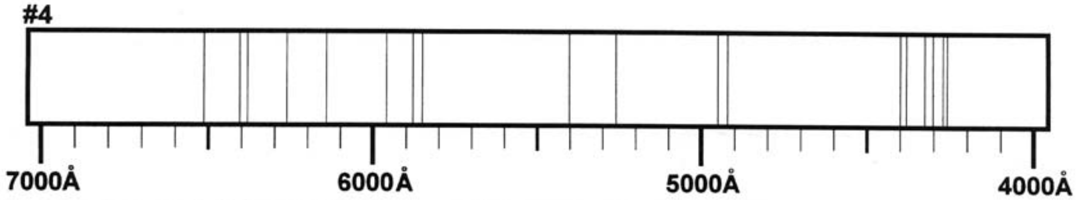
#2



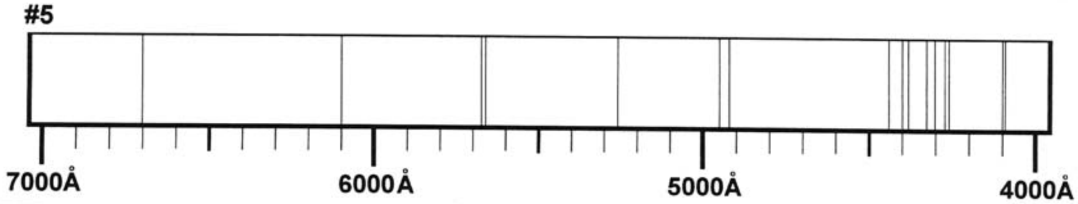
#3



#4



#5



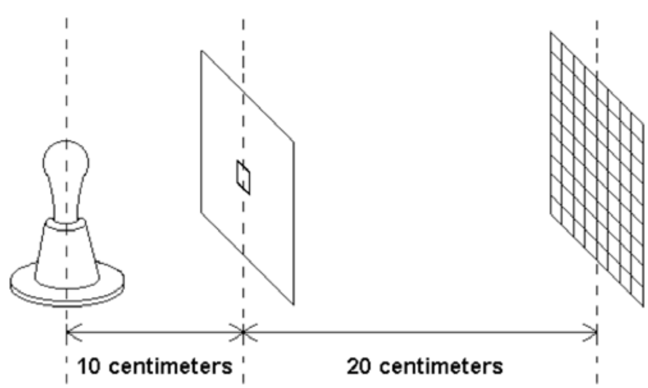
Core Activity 8.3: The Inverse Square Law

If two quantities being compared to each other both increase or decrease correspondingly, we say they are *directly related* to each other. If one quantity increases while the other quantity decreases correspondingly, we say they are *inversely related* to each other.

As the distance from the source of electric fields or gravitation fields increases, the strength of those fields will decrease. This is not a direct relationship, but an inverse one. The strength of electrical and gravitational fields are inversely proportional to the square of the distance from their source. Light intensity follows this same relationship, known as the *inverse square law*. This relationship is a characteristic of most phenomena that radiate out in all directions from a single source, including sound. The inverse square relationship is expressed mathematically as

$$1/r^2 \quad (\text{with } r = \text{distance})$$

Your instructor will give you a piece of cardboard and a piece of paper, each with a small square outlined in the center, along with a second piece of cardboard and a piece of grid paper. Carefully cut out the two squares, leaving no rough edges. Line up the two openings and glue the paper to the cardboard. Next, glue the piece of grid paper to the second piece of cardboard. Your instructor will turn on a clear 200-watt light bulb or other bright source and will darken the room. Have a partner hold the cardboard so that the opening is 10 cm away from the light source, keeping the cardboard perpendicular to the direction of the light. The cardboard will stay in this same location for the entire activity. Hold the grid right up next to the first piece of cardboard, on the side away from the light source, so that the square in the first piece will line up with one of the middle squares of the second piece. (In other words, the distance between the two pieces will be 0.) Keeping the two pieces of cardboard parallel to each other, slowly back the grid-card away from the first card, and record the number of squares illuminated at distances of 20, 30, 40, and 50 cm.



Answer the following questions:

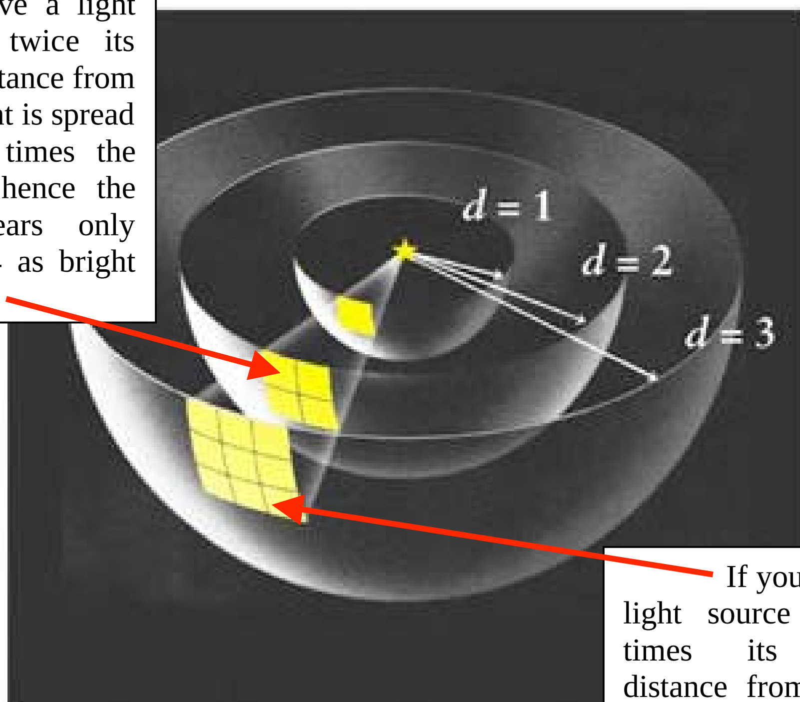
1. For each one of the distances above, what fraction of light was falling on just one of the squares?
2. Can you now calculate what fraction of light would illuminate one square at a distance of 100 cm?
3. In order to have each square receive the same amount of illumination or brightness as it did at 10 cm, how many identical light bulbs would have to be placed at the same location as the original light for each one of the distances in 1 and 2?
4. The planet Pluto is 40 times farther from the Sun than the Earth is from the Sun. If you were on Pluto, how bright would the Sun be compared to how bright the Sun appears from the Earth? How many additional similar Suns would have to be placed next to the Sun for it to shine as brightly on Pluto as it does on Earth?

Cut out this small square carefully.

The Inverse Square Property of Light

Light intensity, like gravity, electromagnetic radiation, and sound, diminishes by the square of the distance.

If you move a light source to twice its original distance from you, its light is spread over four times the area, and hence the light appears only $1/2^2$ or 1/4 as bright as before.



If you move the light source to three times its original distance from you, its light is spread over nine times the area, and it would appear $1/3^2$ or 1/9 as bright as before.

As the distance from the source increases, the radiation continues to spread and its intensity decreases even more, but the amount of energy never quite reaches zero.

This ***inverse square*** *property of light is characteristic of anything that spreads out in straight lines in all directions.*

Poster Page: Inverse Square Relationships

As one gets further and further from a source of electromagnetic radiation, the intensity of the source decreases. As the energy emitted from the source spreads out into space it spreads over the surface of an imaginary sphere of larger and larger radius. Since the surface area of a sphere is proportional to the square of the radius of the sphere (area = $4\pi r^2$), the intensity of the radiation at any point on the sphere decreases as the sphere enlarges. In other words, the intensity of a source of electromagnetic radiation (EMR) decreases with the square of the distance from the source. For example, if we move twice as far from a source, its intensity decreases by a factor of four.

All phenomena which radiate out in all directions from the source follow the same inverse square relationship, including sound, gravity, and electrical forces. Consider the similarities of the two following mathematical equations:

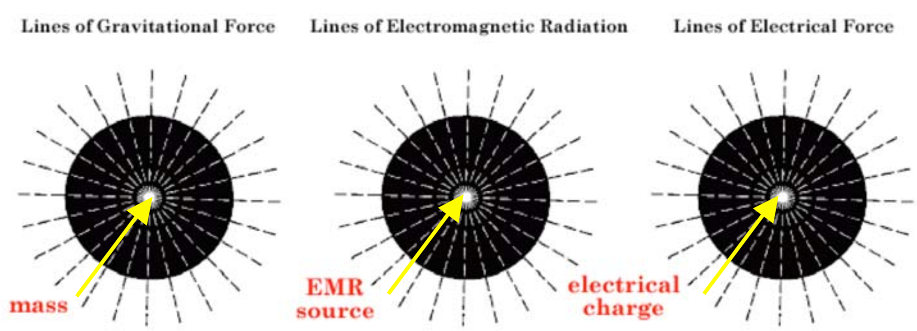
Newton's law of universal gravitation: $F = (G\ m_1\ m_2) / r^2$

This equation states that to calculate the force due to gravity (F) on any object by any other object, multiply the masses of the two objects (m_1 and m_2) and the gravitational proportionality constant ($G = 6.67 \times 10^{-11}$ N m^2 / kg^2), and divide by the square of the distance between the two objects (r^2). Note: A *Newton* (N) is a metric unit of force equal to about one-fourth of a pound.

Coulomb's law for electrical forces: $F = (k\ q_1\ q_2) / r^2$

This equation states that to calculate the electric force between any two objects (F), multiply the amount of charge on the two objects (q_1 and q_2) and the proportionality constant ($k = 9.0 \times 10^9$ N M^2 / C^2), and divide by the square of the distance between the two objects (r^2). Note: A *Coulomb* (C) is the metric unit of charge and is equal to the charge of 6.25×10^{18} protons, i.e., one proton has a charge of 1.60×10^{-19} C.

In the graphic representation of the inverse square law below, you can see that as you draw concentric circles around masses, the lines of gravitational force get farther and farther apart, or weaker. The same decrease in strength happens to radiation and electrical forces as they increase in distance from their points of origin.



Activity 8.4: Light Pollution

Light has been traveling for billions of years, carrying information from remote parts of the universe. But when this ancient light finally reaches the Earth, many of us never see it. It is lost in the glare of *light pollution*. Anyone who lives in or near large cities has seen that the night has been conquered by *skyglow*. For them, the dark, star-cluttered skies of the ancient skywatchers no longer exist. Many people have never seen the clusters of stars and stellar clouds of the Milky Way. Light pollution is a problem for us all, not just for professional and amateur astronomers. Light pollution interferes with everybody's view of the universe.

1. Your instructor will provide a set of slides or pictures showing different types of outdoor lighting. Study the spectra of light sources that you observed in Investigation 8.1 and elemental gases in Core Activity 8.2. Your instructor may provide additional light sources and gas emission tubes.

2. With a portable spectroscope, look at outdoor lighting around your school, home, and/or neighborhood. Determine what types of light sources you see by drawing the spectral patterns you see and comparing them to the ones you drew in class. Draw a map of the area showing where lights are located. Are there areas of bad lighting? Good lighting? Light pollution? Discuss and compare what you find with your classmates.

3. From your observations made in parts 1 and 2 above, discuss what changes you would recommend to improve lighting and reduce the amount of light pollution in each particular lighting situation.

SPACE TALK

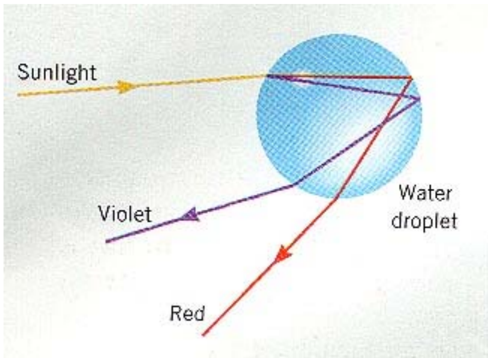
Iris was the Greek goddess of the rainbow. Her appearance was associated with tumult and mischief for humans, and considered an omen of war and storms. She was the daughter of Thaumus, the god of wonder, marvel, and magic. The rainbow is certainly a marvelous and magical thing to behold, a subject for poets, painters, and photographers, as well as for meteorologists and physicists. Understanding some of the physical properties of light that produce this colorful array can help us see that the paintings and pictures depict something that isn't really there. The rainbow is only one manifestation of the ways the properties of light deceive our senses. The seven colors of the rainbow are as imaginary as the pot of gold at its end.

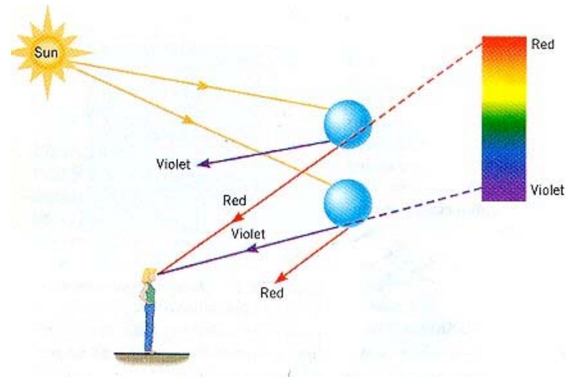
The man who first understood the physics of the rainbow was Theodoric of Freiberg, who lived in the latter part of the 13th century. After meticulous study, Theodoric concluded that the rainbow was produced by the **dispersion** of light into separate colors by individual raindrops. Since gravity pulls raindrops to the ground and rainbows don't fall out of the sky, he further decided that falling raindrops are continuously replaced by other raindrops and the eye cannot detect the motion of the changing raindrops producing the image. Because raindrops are difficult to study in the lab, Theodoric substituted crystalline stones to make a model of rainbows. Although Theodoric could produce the visible **spectrum**, he did not know what caused the individual colors to appear.

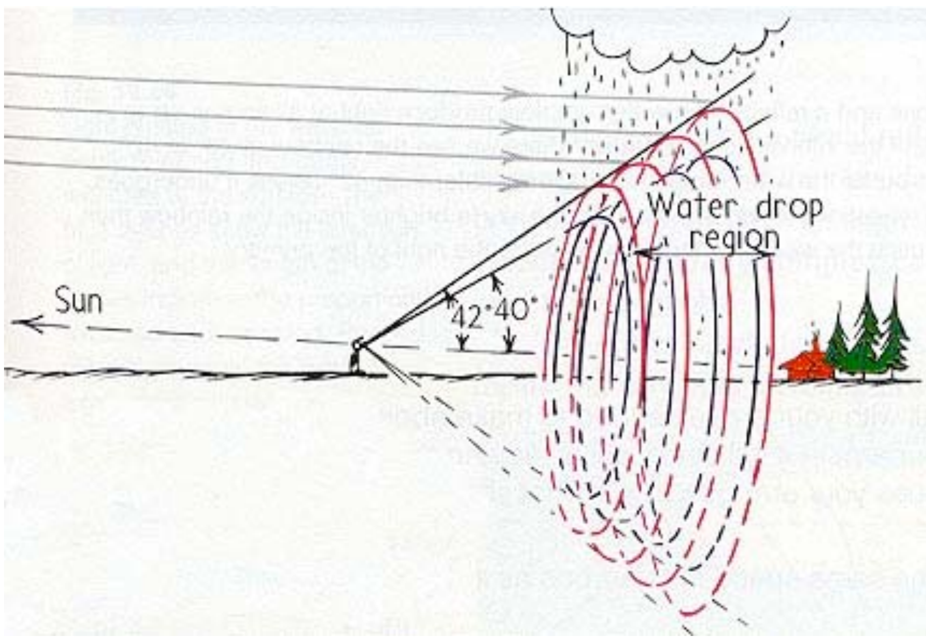
When you see a rainbow, the falling raindrops are usually ~1.6 to 2.4 km away from you, and the Sun is always behind you. The rainbow appears as a circular arc, beginning and ending at the horizon. A straight line drawn from the Sun, through your eyes, and through the Earth to the center point or radius of the arc, will end at the location of the *antisun*, or **antisolar point**. This line represents an axis through the center of the rainbow, which appears at a 40°–42° angle from the axis. You only see one piece of the rainbow, which is actually an entire circle. The lower the Sun sets, the higher the antisun rises above the horizon. The higher the antisun rises, the greater the amount of arc or circumference that can be seen, until a full semicircle can be seen at sunset. When the Sun is higher than 42° in the sky, the entire rainbow disappears below the horizon; during summer solstice at latitudes lower than 42°, rainbows can never appear in the middle of the day (see diagram on following page).

The fact that the rainbow always appears to be perfectly round is evidence that is not a tangible object. The arc always looks as if it is exactly in front of the observer. If it were really there, it would appear in more elliptical shapes to other observers standing on either side. Each observer is actually seeing a different rainbow. If one hundred people are observing a rainbow, there are one hundred different rainbows in the sky. If you walk along while watching a rainbow, it moves along with you, always at 40°–42° from the axis between the Sun and antisun. If you walk towards the rainbow, it retreats from you. If you back away, it moves forward. Since the rainbow is an illusion, has no end, and changes position as you move, that pot of gold will forever elude you.

When white light from the Sun enters a spherical raindrop, the light is *refracted* or bent. The amount of **refraction** is different for each **wavelength** of color, so each color is bent by different amounts. When the wavelengths of light reach the back of the raindrop, they are *reflected* back towards the front of the raindrop. The **reflection** of the wavelengths







does not change their angle, they do not get bent. At the surface of the raindrop the wavelengths emerge and once again get refracted or bent as they travel into the air. Wavelengths always get refracted when they leave or enter a medium which has a different density from the medium in which they were traveling. Each raindrop disperses a full spectrum of colors. Yet an observer on the ground, facing away from the Sun, sees only one color of light coming from each raindrop. If you see red light from a raindrop, the violet light from that drop is being deflected above your head. Further down you can see violet light coming from the raindrops; the red light from these drops is being deflected below your eyes into the ground. You see red light when the angle of the axis from the Sun to the antisolar point is at a 42^{o} angle to the observer, and violet light when the angle is 40^{o}. Other wavelengths of color are seen at intermediate angles between 40^{o} and 42^{o}.

The colors of the rainbow gradually blend into each other. Rainbows display a wide range of colors, and a rainbow can even change colors while you are watching. There are not equal amounts of each color, and their intensities are also not equal. Whether the colors appear bright or dull depends on atmospheric conditions. Since rainbows are always the same distance from you, and visible light follows the **inverse square law** just like all **electromagnetic radiation**, brighter colors are not the result of more light reaching you. The order of colors is always the same, red at the top followed by orange, yellow, green, blue, and violet. (Isaac Newton also included the color indigo between blue and violet.) If you watch a rainbow during a thunderstorm, pay close attention during the sound of thunder. The boundaries between the colors will blur and disappear as a result of vibrations of air molecules which cause the raindrops either to vibrate or to merge together.

Rainbows are merely a beautiful illusion created by three of the wavelike properties of light: reflection, refraction, and dispersion. Because of their jewel-like brilliance, rainbows have often been portrayed in mythology as dispensers of wealth, such as gold, silver, or pearls. Many cultures, however, have regarded the rainbow as having malevolent aspects. In Greek mythology, Zeus instigated the renewal of the quarrel between the Trojans and the Greeks, then spread a rainbow across the sky to announce the outbreak of war. Celtic legends portray the rainbow as a snake with flaming eyes. The Celts believed that the devil assumed the snake disguise when he came to Earth and dried up all the lakes to satisfy his thirst. Aboriginal Australian lore also associated a serpent with the rainbow, and thought it responsible for bringing disease. They believed, too, that gods resided in the sky on crystal thrones, and the only way to reach them was to climb up a rainbow. In some places across Europe, it was considered dangerous to point at a rainbow—one's finger could become inflamed or lost, depending on the prevailing mood of the rainbow deity. Sailors thought if they sailed by one end of the rainbow while it was thought to be taking in water, they would be swallowed also.

Early cultures did not know that the rainbow is not a real object. Now it is described and modeled by complex mathematical equations, and explained in textbooks on physics and optics. Nevertheless, the rainbow, an elusive apparition of light, has not lost its allure.

One of the most important dragons of creation mythology is the Australian Rainbow Serpent, its symbol being the rainbow bridging Heaven and Earth. The Australian Aboriginal people believe the universe has two aspects - the physical world in which we live and another connected world from which it is derived called the Dreamtime. Since the Dreamtime is connected to our world, the creation story of the Ancestors and their mythical past is simultaneously the creation of the present and the future. There are as many legends of the Rainbow Serpent as there are tribes of people.

The Rainbow Serpent

Unit 4: THE MESSAGE OF LIGHT

Except for meteorites and a few samples of Moon rocks and soil brought back by Apollo astronauts, we have no physical materials from celestial objects in or beyond the Solar System. Yet we have considerable knowledge of these objects, even though they may be up to billions of light years away. One way that astronomers "observe the universe" is through electromagnetic radiation (EMR), commonly referred to as the electromagnetic spectrum. Visible light is only one part of the spectrum that opens up windows to the universe. All parts of the spectrum offer us unique information. Analysis of the spectrum gives astronomers a vast amount of information about stars, including age, mass, composition, temperature, luminosity, and evolutionary history. Chapter 8, "The Nature of Light," discusses the physical properties of electromagnetic radiation. Chapter 9, "The Life of a Star," explains how spectroscopy, the study of electromagnetic radiation, gives us the information we need to determine the evolutionary stage of a star.

CONTENTS FOR UNIT 4

CHAPTER 8: THE NATURE OF LIGHT

An introduction to the basic physics of light and the rest of the electromagnetic spectrum, and how spectroscopic analysis of the colors within visible light gives information about chemical composition.

CHAPTER 9: THE LIFE OF A STAR

This chapter introduces the Hertzsprung-Russell (H-R) diagram, a graph depicting the stellar spectral types that represent the evolutionary stages of stars.

Relationship to National Science Standards and Benchmarks

Unit 4 addresses the knowledge of light, energy properties and transformation, and the Sun's energy, as stated in the *Physical Science* content standard for eighth grade students. The *Physical Science and Earth/Space* content standards for twelfth grade students requires knowledge of nuclear fusion, nucleosynthesis, atomic structure, gravitation, and the generation and interactions of the electromagnetic spectrum. The process by which the historical perspective of science knowledge changes or becomes more complete by evolving over time is highly evident. Evolutionary processes within the universe as described in the *Earth and Space* content standard for grades 9–12 are emphasized. The content dealing with the life cycles of stars covers key concepts related to the *Common Themes and Unifying Concepts,* and the content relating to the classification of radiation and stars by physical properties emphasizes the specific unifying concept of *organization.* This unit stresses the concept that scientific ideas depend on experimental and observational confirmation, and shows students that science helps drive technology as it addresses questions that need more sophisticated instruments, and provides principles for better technology and technique. All students are expected to understand that technology is essential to science, as it enables observations of objects that are otherwise unobservable due to factors such as distance and time. Science and technology are reciprocals, as stated in the *Science and Technology* content standard. Technicians have developed instruments to enable astronomers to "see" the visually unseeable. More refined technological tools with which to observe the universe help all scientists to obtain new information and to revise their ideas accordingly. Utilizing specialized technology to collect and analyze data, determining a classification system, and plotting properties in graphical form enables scientists to understand large-scale and long-term phenomena.

Chapter 8: The Nature of Light

Summary

An introduction is given to the basic physics of light and the rest of the electromagnetic spectrum, the means by which astronomers learn about the universe. The forms of electromagnetic radiation differ only in wavelength, but this dramatically affects their properties and the methods that we use to detect them. Light is composed of a full spectrum of colors which gives information about the stars. As light is emitted from the surface of stars into space it follows the inverse square law relationship.

Terminology

antisolar point	inverse square law	skyglow
absorption lines	light pollution	spectroscopy
Balmer series	Lyman series	spectrum
dispersion	microwave band	wavelength
electromagnetic radiation	photons	wave-particle duality
emission lines	reflection	
ground state	refraction	

Common Misconceptions

1. *Light is clear and prisms or gratings "add" color.*
2. *There is a linear relationship between distance and apparent brightness.*

SUGGESTIONS FOR POSTER PAGES, INVESTIGATIONS, AND ACTIVITIES

Investigation 8.1: The "Flavors" of Light

Color is important in stellar analysis. Give the students an assortment of objects with which to investigate light. Feathers, prisms, diffraction gratings, and hand-held spectroscopes are good tools. For younger students, feathers are a fine introduction to the spectrum, as they make excellent "prisms" and produce a spectrum when light passes through them. (They can be obtained from hobby shops or craft stores, or from pillows.) Have the students look closely at the feathers (later on they may conclude that the fine, interlocking structures are similar to a diffraction grating and that the fine lines allow the colors to separate), and then turn on a light bulb and have the students examine how light is affected by its passage through the feathers. Does rotating the feathers change the colors? Are big feathers better than smaller ones? What colors are seen? Do they change? Have student write descriptions and draw colored pictures of what they see and then discuss their results with the rest of the class.

Students can also look through diffraction gratings (see Resource List for details). If they do, have different light sources available, such as incandescent and fluorescent. Have them experiment with prisms. They can draw spectra they have observed using feathers, gratings, and prisms and compare the results. Which one produces the “best” range of color? NOTE: A clear, cylindrical, refrigerator bulb (with a linear filament) works very well with transmission gratings. RESOURCE

At this time you may want to introduce a hand-held spectrometer, which not only separates light into its spectrum of colors, but also shows the intensity of each of the colors present. This will be investigated further in the spectroscopy activity below, and in even greater detail in analyzing stellar spectra in following chapters. Older students may not need the investigation as an introduction. Inexpensive spectrometers can be obtained from Project Star (see Resource List for details). RESOURCE

Core Activity 8.2: Spectra of the Elements

You will need spectroscopes, spectrum tubes of elemental gases, and a voltage source for part A of this activity. The Project Star spectroscopes work well. Physics labs usually have spectrum emission tubes and voltage sources. If the spectrum tubes are not available, then have students look at different light sources around the school and at home. They will still be able to do part B. You can either make transparencies of the individual spectra for them to overlay on the mixed spectra, or they can simply fold the paper for each individual spectra and place them above or below the mixed spectra to match up the spectral lines.

Answers to Spectra Identification Problems

1. Hydrogen and magnesium.

2. Hydrogen, helium, and lithium.

3. Nitrogen and mercury.

4. Neon and iron.

5. Nitrogen, lithium, and iron.

Core Activity 8.3: The Inverse Square Law

Unless you are dealing with older students, precut the squares in the paper and the cardboard. The edges must be sharp and smooth or the outline of the illumination of light on the grid will be difficult to see, and the room must also be quite dark. Templates are included in the student activity.

Answers to questions:

1. 1/4,1/9, 1/16, 1/25

2. 1/100

3. 4, 9, 16, 25, 100

4. 1600

Poster Page: Inverse Square Relationships

Most students perceive the change in intensity of a light source with distance as linear. We are so used to thinking of light as moving in straight lines that we forget light leaves a source in all directions. In textbooks the movement of light is usually designated as one or two rays represented as arrows, which further reinforces the misconception. Light is only one part of the electromagnetic spectrum. All parts behave in the same way, from radio waves to X-rays and gamma rays. The inverse square law applies to any equation that has distance squared in the denominator, though students often fail to recognize similarities among equations. Electrical forces, gravitational forces, and EM radiation all decrease with the square of the distance, whether the distance is in light-years, kilometers, or angstroms. Radii also are distances; the larger the radius of a star, the larger the surface area and the less radiation that leaves per unit area. The apparent size also varies inversely with distance. The students are given the equations for electrical and gravitational forces.

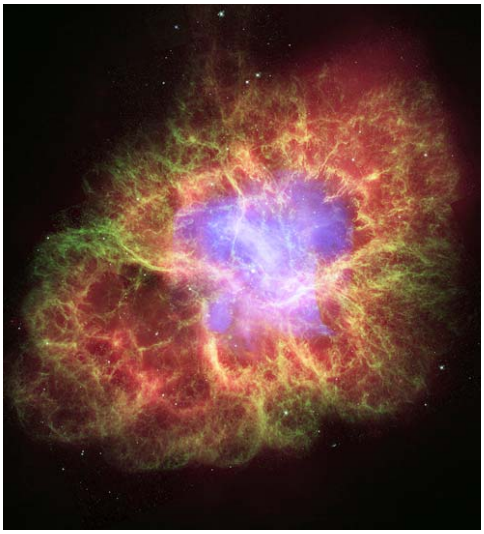
Poster Page 4.2, "Astrology or Astronomy?" discusses horoscopes and the supposed influence of stars and planets in determining human characteristics and destinies. Have students use Newton's Law of Universal Gravitation and plug in the numbers for the planet associated with their horoscope. Then they can use other planets, the Sun, or people, and calculate how much gravitational force these different objects exerted on them at the moment of their birth. The results are always interesting.

Activity 8.4: Light Pollution

The International Dark Sky Association (IDA) has a set of slides available concerning light pollution. They will also provide a complete set of articles and information for a very reasonable price. (See Resource List for details.) From other sources you can also obtain remarkable satellite photographs of the Earth at night, which graphically depict the extent of light pollution. (See Resource List for details.) Students can study light pollution problems in their own location. Students can determine related factors such as the energy cost of inefficient lighting, the politics and budgetary considerations to improve lighting and reduce light glare and trespass, city lighting ordinances, the effect of lighting on crime levels, and psychological factors dealing with lighting. Who establishes criteria for lighting? What factors are considered? The IDA materials are a rich resource for these types of research. Your students might initiate a study and approach the local government to try to change a light pollution problem in their area.

RESOURCE

Chapter 9: The Life of a Star



The Crab Nebula and Pulsar Composite Image (Chandra, Hubble, Spitzer)

Introduction

Massive stars explode when they die, releasing as much light as an entire galaxy of stars. Such an explosion is called a *supernova*. It can catapult a star from obscurity to spectacular prominence in the night sky. A supernova that occurred in the year 1006 (SN 1006) shone so brightly that objects could be seen by its light for weeks. A Muslim astrologer, Ali ibn Ridwan of Cairo, recorded the event. So did a monk named Hepidannus, of St. Gall, Switzerland. The records of these two men locate SN 1006 in the direction of the constellation Lupus in the Southern Hemisphere. Japanese and Chinese sources more precisely locate the supernova near kappa Lupi and one degree west of beta Lupi. It was the brightest star observed in all of recorded history. It was probably visible for three months during daylight, and only after three years did it fade below naked-eye visibility at night. The remnant left behind from the explosion has a low luminosity and large size, and is the faintest remnant of the five well-established historical supernovae seen during the last one thousand years. The remnant emits in the radio and X-ray bands and is thought to be 2300 light-years away.

On July 4, 1054, Chinese and Japanese astronomers recorded a bright star in the constellation Taurus which had not been visible before. At maximum brightness it was comparable to Jupiter, and remained visible to the unaided eye for 653 days in the night sky. No definite historical accounts of SN 1054 have come to light in Europe. However, it seems to have been observed and recorded in the rock art of the American southwest. An unusual picture exists in Chaco Canyon, New Mexico, painted on a rock panel with red hematite. The picture depicts a crescent shape not seen elsewhere in the canyon and which is clearly associated with a “bright” star. The star is stylistically unlike the typical Pueblo stellar representations. The rock panel is located in a Sun-watching shrine. It seems likely that the Sun-priest, whose duty it was to observe the daily sunrise, was struck by the spectacular association of the waning crescent Moon and the bright supernova and recorded it on the spot. On July 4, 1054, the crescent Moon would have been in the direction of Taurus. Representations of the same conjunction of a crescent moon and a bright star have been found at several other sites from Texas to California. The remnant left behind by SN 1054 is the Crab Nebula, and is a strong radio source known as Taurus A. In the center is a rapidly rotating pulsar with a period of 33 milliseconds.

On the evening of November 11, 1572, as Tycho Brahe was returning home from his chemistry lab, he saw a bright, unfamiliar star in the constellation of Cassiopeia. He hurried to get his sextant, and measured the distance of the star from the well-known stars in Cassiopeia. He made hurried notes as to its magnitude, color, and other characteristics. After several nights of observation, Tycho determined that it had no motion and was therefore a fixed star. It was more brilliant than Sirius and probably equal to Venus at its brightest. The star remained visible for seventeen months, until March 1574. Tycho compiled his observations and notes about the new star, and had them published. *De Novâ Stellâ* was his first publication and established his reputation as a scientist and scholar. Tycho's observations of SN 1572 were the beginning of his career as an astronomer. Both the supernova of 1054 and Tycho's supernova of 1572 were visible in daylight to anyone who knew they existed; however, neither was so bright as to attract the attention of the untrained eye.

In October 1604, a supernova appeared in Ophiuchus. The star became as bright as Jupiter, then faded from naked-eye visibility a year later. The most complete account of the supernova was given by Johannes Kepler. The optical remnant of SN 1604, seen as little patches of wispy nebulosity, was not detected until 1943.

SN 1987A was the first naked-eye supernova since 1604, and occurred in the Large Magellanic Cloud, approximately 160,000 light-years away. For the first time, Earth-bound astronomers had the technology and telescopes to observe the cataclysmic demise of a star across the entire electromagnetic spectrum. The event was noticed three months before maximum brightness, allowing the scientific community to determine if the explosion corresponded to predicted theories of violent gravitational collapse. SN 1987A peaked at 3rd magnitude three months after exploding and now, more than ten years later, has faded to a magnitude of +20. Studies are still being conducted on the gases shed and stellar winds produced during the stages before final collapse, and on the rapidly expanding remnant itself. The results will increase our knowledge of how a supernova produces and disperses elements into the interstellar medium.

Supernovae have an important role in the composition of matter. They are sites of nucleosynthesis, the production of new elements by nuclear fusion. These elements are thrown into the surrounding space and eventually become incorporated into other stars. Our own Solar System contains traces of supernovae that exploded before the Sun and planets formed. All elements on Earth, such as the iron found in hemoglobin, calcium in teeth, and the gold and silver that become jewelry, were originally manufactured in the cores of stars.

The red supergiant stage, which precedes a supernova explosion, may last for 100,000 years. Even though there are several supernova candidates in the galaxy, it is hard to tell how far any particular star is along the path to destruction. One such candidate is Betelgeuse, a red supergiant in the right shoulder of Orion that is 300 times larger than the Sun. It is surrounded by faint shells of dust which were apparently ejected from the star 50,000 to 100,000 years ago. Because the supergiant stage probably lasts only about 100,000 years, Betelgeuse may be quite close to the supernova explosion that will end its life. It may happen tomorrow or in 50,000 years. Since Betelgeuse is 410 light-years away, it will take that long for the information to reach us. Maybe it has happened already and we don't yet know. A supernova so close to Earth would create an extraordinary spectacle in the sky, visible even during the day and outshining every other star.

To access a set of activities, materials, and resources on stellar evolution: *Stellar Evolution* at http://chandra.harvard.edu/edu/formal/index.html

Investigation 9.1: The Continuous Spectrum

Your instructor will provide a large continuous spectrum. How many colors are visible? Indicate the color boundaries. The wavelengths you are observing range from approximately 4000 to 7000Å. Measure the entire length of the spectrum in centimeters and determine the scale of your spectrum in Å /cm. Measure the length of each color and determine how many angstroms to which they correspond. Do your answers agree with the accepted values in Table 8.1? If not, what might be some reasons why? Is radiation being emitted that is not part of the visible spectrum? If so, what type? Where would you place it on your spectrum?

The Radiation Laws

All objects emit some type of electromagnetic radiation. The radiation laws describe both the amount and the wavelengths of radiation emitted by an object, which depend only upon its temperature. Since there is no such thing as a perfect reflector, all objects absorb some type of radiation. That radiation must then be emitted, or the object's temperature would continuously increase. Not all objects absorb or emit energy in the same way: some are more reflective or have a greater capacity for absorption. Some also transmit various wavelengths with their corresponding amounts of energy. A theoretical model, called a *black body*, is defined as the perfect absorber and radiator. Black bodies do not reflect any radiation, but rather absorb all radiation that falls on them and then radiate it all away. Stellar atmospheres are good approximations of black bodies. They absorb all the radiation rising from the core, and then emit the radiation into the surrounding space. Stars, like hypothetical black bodies, follow the three radiation laws: *Planck's law*, *Wien's law*, and *Stefan-Boltzmann's law.*

Black body radiation is thermal radiation emitted from a black body at a particular temperature. When an object is heated until it glows, it emits all wavelengths, or colors, of the visible spectrum. However, there is always one dominant, or peak, wavelength emitted that depends upon the temperature of the object. An object heated to 3000K emits radiation whose peak wavelength falls in the infared or near-infrared part of the spectrum. A 6000K object has a maximum wavelength output in the yellow; 12,000K is greenish, and 24,000K is in the ultraviolet or near-ultraviolet region of the spectrum. At lower or higher temperatures, the maximum wavelength output falls outside the visible spectrum. Therefore, the temperature of an object determines the dominant wavelength being radiated, which corresponds to a particular color. The continuous radiation from a star does not follow theoretical black body radiation exactly; however, it is similar enough to apply the black body radiation laws.

Planck's law describes the shape of the radiation curve of a "perfect radiator," which is represented graphically below in Figure 9.1. In analyzing the graph, the three major points of this law become apparent:

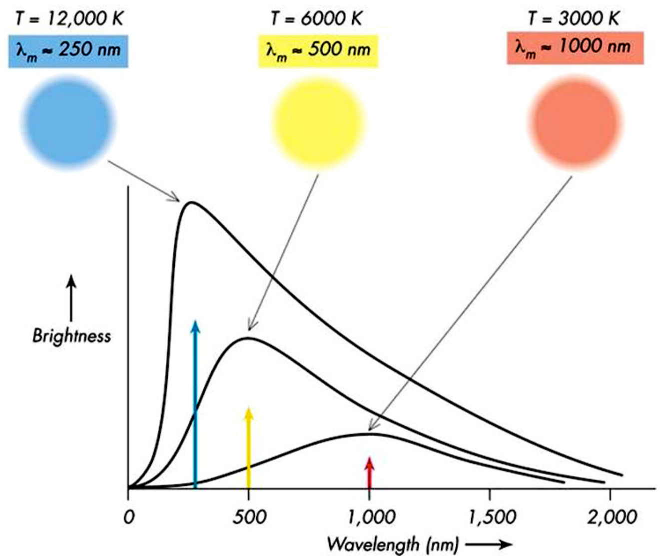


Figure 9.1

1. Any black body emits energy at every wavelength but not in the same proportions.
2. A hotter body produces more energy at every wavelength than a cooler body of the same radius and mass.
3. The hotter the body, the shorter the frequency of the dominant wavelength emitted; color depends on temperature.

Wien's law is simply a mathematical statement of point #3 of Planck's law. From the graph in Figure 9.1, a 3000K object produces a maximum wavelength peak at about 9500Å, and a 6000K object peaks at about 5000Å. Therefore, Wien determined that

$$\lambda_{max} = \frac{2.9 \times 10^7}{T}$$

where T is the temperature in kelvin, λ is the wavelength of maximum output in angstroms, and 2.9×10^7 is Wien's displacement law constant in angstroms. (Note: A *constant* is a number which represents the proportionality between two different units. In the above relationship it allows temperature in kelvin to be turned into the equivalent wavelength in angstroms.)

Astronomers can determine the maximum wavelength output by using an instrument called a spectrophotometer, which measures the intensity of all the wavelengths of radiation emitted by a star. The maximum intensity is then put into Wien's relationship to calculate the temperature of the star.

Stefan-Boltzmann's law is also easily understood by looking at Figure 9.1. The total energy emitted by a star at a specific temperature, such as 24000K, is equal to the area under the radiation curve for that temperature. In mathematical terms, the following relationship gives the energy emitted per unit area of body surface:

$$E = \sigma T_{eff}^{4}$$

where T_{eff} is the effective temperature in Kelvins; E is the energy per unit surface area in erg/cm^2; σ is the Stefan-Boltzmann constant, equal to 5.70 x 10^{-5} erg/cm^{-2}sec^{-1}K^{-4}. (An *erg* is a metric unit used for smaller amounts of energy than a Joule.)

The *effective temperature* is the best measure of the actual temperature of the gases in a star's outer layers. The effective temperature of a star is equal to the temperature of a black body having the same radius and radiating the same amount of energy as the star. Therefore, T_{eff} can also be stated as a function of the radius and power output as follows to calculate the total output of a star:

$$L = 4\pi R^2 E = 4\pi R^2 \sigma T_{eff}$$

where L is the luminosity, or total energy output per second; R is the radius of the star; T_{eff} is the effective temperature in Kelvin, and $4\pi R^2$ is equal to the area.

The Sun emits the entire spectrum of electromagnetic radiation (EMR), from X-rays through radio waves. Nearly 100% of the radiation is in the infrared, visible, and near ultraviolet range; shorter wavelength ultraviolet, X-ray, and radio bands comprise a small fraction of the total. The photosphere is the "visible" surface that we see, and it has a surface temperature of 5770K. This temperature corresponds to a wavelength of ~5500Å, which lies in the yellow-green part of the visible spectrum. Sirius has a surface temperature of ~12,000K and also emits the entire range of EMR. With its higher temperature, Sirius will emit more of every single wavelength than the Sun. Its maximum wavelength output will be of a high frequency and is in the blue end of the spectrum. The same overall result holds for all stars that are the same size or larger than the Sun, and have a higher temperature.

Stellar Classification and the Hertzsprung-Russell Diagram

Stars are classified by temperature or spectral type from hottest to coolest as follows:

O B A F G K M R N S

(Sometimes R and N stars are grouped together into spectral type C.) These categories are further subdivided into subclasses from hottest (0) to coolest (9). The hottest B stars are B0 and the coolest are B9, followed by spectral type A0. Each major spectral classification is characterized by its own unique spectra. Stars of spectral type G, like our Sun, have an effective surface temperature of 5000 to 6000K, with a maximum peak output that falls in the yellowish-green part of the spectrum, and have the strongest double calcium lines of any spectral type. Spectral lines can show different characteristics within the same spectral type, and so a second type of classification system for stars was devised using luminosity. The differences in spectral lines among stars having the same spectral type is a function of the radius of the star, which results in different luminosities. *Luminosity* (L) is related to the absolute magnitude of a star, and is equal to the total outflow of power. Two stars with similar effective temperatures but greatly different luminosities must differ in size: they belong to different luminosity classes within that spectral type, as determined from their spectra. The Sun is assigned the value of one solar luminosity. Stellar luminosities range from one million times more luminous than the Sun, to one ten-thousandth of the luminosity of the Sun.

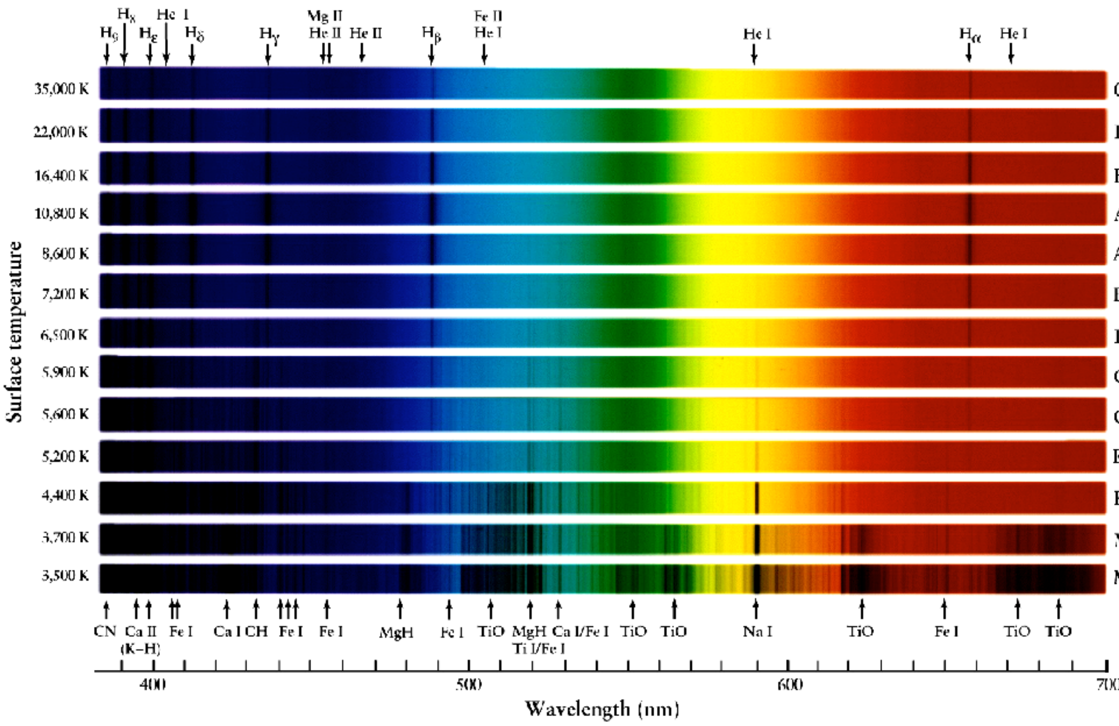


Figure 9.2 Stellar Spectra

The light sources and spectrum tubes you studied with a spectroscope produced bright emission lines. This is because there were no thick layers of atmosphere to interfere with the emission lines. Stars, unlike tubes of elemental gases, produce *absorption lines* because the outermost layers absorb radiation from the core. Because a star is like a black body, it absorbs the radiation and then emits it into the surrounding space. This radiation is emitted over a range of wavelengths, so we see dark lines, called absorption lines, where the radiation is “missing.” All stars have a similar basic chemical composition; differences between spectral types are due only to the different effective temperatures. Hydrogen produces dominant spectral lines in stars with an effective temperature near 10,000K. At this temperature, electrons of the hydrogen atoms are becoming excited and then undergoing de-excitation and transiting down to the second energy level, or Balmer line, giving off photons in the visible part of the spectrum. At hotter temperatures, most of the hydrogen is ionized—the electrons have been stripped away. There are fewer intact hydrogen atoms to produce the characteristic spectral lines. The few hydrogen atoms that have managed to retain their single electron are mostly in such highly excited states that their spectral lines are invisible, since they fall back down to the the Lyman line (ground state) and emit photons in the ultraviolet part of the spectrum. Only the few neutral atoms of hydrogen that manage to retain their electrons and are not in a highly excited state can absorb and re-emit visible radiation. Since there are fewer electrons that can fall back down to the Balmer line, there are fewer photons emitted in the visible part of the spectrum and the absorption lines are weaker than in cooler stars.

Cooler stars, such as the Sun (surface temperature of 5770K), are not hot enough to excite the hydrogen atoms. The electrons remain mostly in the ground state and produce only very faint absorption lines. Cool red stars with surface temperatures of a few thousand kelvins show extremely weak hydrogen lines. Their spectra contain many absorption lines produced by molecules rather than elements, as they are so cool that even molecules can remain intact. Although stellar spectra vary widely in the strength of hydrogen absorption lines, it is due to the effective surface temperature of the individual star, and not a difference in the amount of hydrogen present (see Figure 9.2).

When stars are plotted on a graph of luminosity or absolute magnitude versus spectral classification (temperature), the results reveal the evolutionary stages of the stars. This graph is called the Hertzsprung-Russell, or H-R, diagram. You have seen that the temperature is easily obtained by determining the wavelength of radiation of greatest intensity from spectrophotometry. Absolute magnitude is defined as the brightness of a star at a distance of 10 parsecs from the Sun. The absolute magnitude can be obtained from a mathematical relationship called the *distance modulus*, a relationship involving apparent magnitude, absolute magnitude, and distance of a star. The apparent magnitude is determined visually, and if the star is close enough to determine its distance through parallax, the absolute magnitude can be derived from the following equation:

$$\mathbf{M = m - 5\log_{10} (r/10)}$$

where m is the apparent magnitude, M is the absolute magnitude, and r is the distance in parsecs.

If stars are too distant to measure their parallax, we must use other techniques, such as the period-luminosity relationship of Cepheid variable stars. With Cepheids, apparent and absolute magnitudes can be determined, and then the distance can be calculated with the distance modulus.

In considering the H-R diagram above (Figure 9.3), notice that the distribution of stars is not random throughout the graph. The stars follow certain trends, and there are some places where no stars exist.

Starting at the upper left-hand corner and curving down to the lower right-hand corner is a band called the *main sequence*. 90% of all stars lie within the main sequence. These stars run from the hot and bright O and B stars at the top left-hand corner to the cool, dim K and M stars at the lower right-hand corner. Main sequence stars have a fairly steady rate of fusion of hydrogen going on in their cores. The Sun is a main sequence G2 star. At the top of the diagram is a band of stars that have a high luminosity but may be cool in temperature. In order for this relationship to occur, these stars must have a large surface area; these are the *red giants* and *supergiants*. In the lower left-hand corner runs a band of objects which are extremely hot with a low luminosity. These objects must be very small to have such a low luminosity. They are called *white dwarfs*, and are the end products of the collapse of stars with a mass similar to the Sun. White dwarfs, red giants, and supergiants represent different evolutionary stages in the life of a star. In main sequence stars, the force of radiation pressure pushing outward from the fusion process is balanced by the inward pull of gravitational forces. When hydrogen, the fuel for nuclear fires, begins to run out, the two forces become unbalanced. The star then begins a series of stages as it begins to die. We can see this process represented by stars outside the main sequence in the H-R diagram.

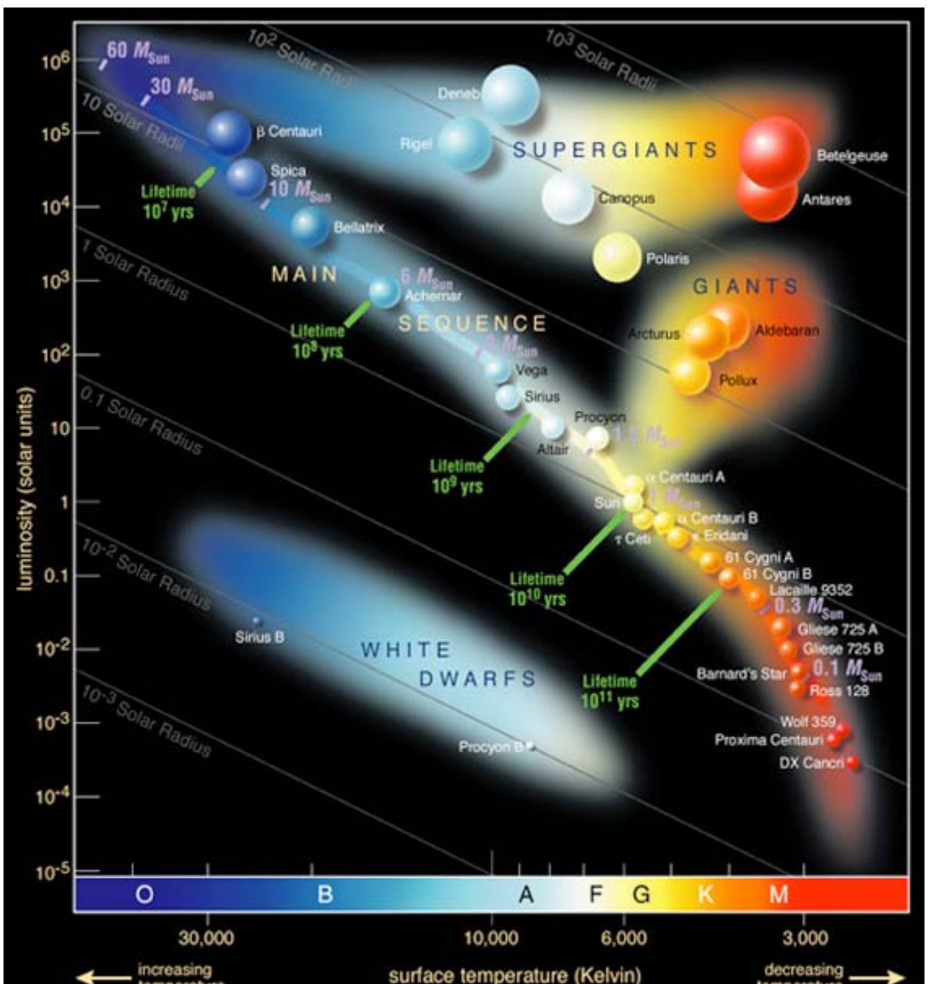


Figure 9.3 H-R Diagram

"The most original thinker of all..."

Antonia Caetana de Paiva Pereira Maury (1866-1952) was born in Cold Spring, New York. She was the granddaughter of John William Draper and niece of Henry Draper, both prominent physicians who were also noted amateur astronomers specializing in astrophotography. In fact, it was the stellar spectra work of Henry Draper which eventually led to Antonia's career at the Harvard College Observatory (HCO). Not long after graduating from Vassar in 1887 with honors in astronomy, physics, and math, Antonia enthusiastically accepted a position at the Observatory, where she worked on and off until 1935.

Antonia joined the HCO during the Henry Draper Memorial project, a monumental stellar classification project. Her intellect and education made her especially well-suited for the task of re-evaluating the new and greatly improved stellar spectra photographs. Maury independently established her own system for the classification of spectra. She reordered some of the original spectral classes to represent a sequence in temperature and decided that they were inadequate to describe the complexity of the spectral lines she saw. She therefore added a second "dimension" to the system-a letter which described the appearance of the spectral lines: `a' for wide and well-defined; `b' for hazy but relatively wide and same intensity as `a'; and `c' for spectra in which the H and "Orion lines" (now known to be due to helium) were narrow and sharply defined, while the calcium lines were more intense. She also had a class `ac' for stars having characteristics of both `a' and `c'. *The Henry Draper Catalogue* finally appeared in print in 1897, and in it Maury emphasized the importance of the `c characteristic,' which she firmly believed represented a fundamental property of the stars. This was due to different luminosity classes of the stars. Her work was later praised by Hertzsprung.

> *Marvelling at the vast expanse of the known universe, she wistfully philosophized, "But the human brain is greater yet, because it can comprehend it all."*
>
> -*"Antonia Maury"* in **Maria Mitchell's Famous Students**, by Dorrit Hoffleit.

Antonia Maury was the first to determine the period of the first spectroscopic binary star, Mizar-discovered by HCO Director E. C. Pickering in 1889. That same year Maury discovered the second spectroscopic binary, beta Lyrae. This type of star-whose duplicity is known through irregularities in its spectra-soon became her main interest in astronomy, and she would spend many years studying photographs of the stellar spectra of these stars. She not only was the first person to find the orbital periods of these double stars, but she also was the first person to compute their orbits. She devoted most of her attention to her favorite, and spectroscopically very complex star, beta Lyrae. According to astronomer Dr. Dorrit Hoffleit, Antonia Maury "was the most original thinker of all the women Pickering employed; but instead of encouraging her attempts at interpreting observations, he was only irritated by her independence and departure from assigned and expected routine."

Colonel John Herschel called Maury's work on spectroscopic binaries "one of the most notable advances in physical astronomy ever made." She was appointed Pickering Fellow for 1919–20 to aid in her spectroscopic work. After her official retirement from Harvard in 1935, she continued to visit the observatory yearly to check on observations of her final project, the enigmatic double star, beta Lyrae. In 1943, the American Astronomical Society awarded Antonia Maury the Cannon Prize for her work on stellar spectra.

Not only was Antonia Maury an accomplished astronomer, but she was also a dedicated naturalist, a recognized authority on birds, and a conservationist of historical sites and of natural resources.

Hertzsprung *and* Russell

In 1905 an amateur astronomer and photographer in Denmark, Ejnar Hertzsprung, studied the relationship between a star's color and its absolute brightness, or luminosity. He expressed color as a star's spectral class, and expressed luminosity as absolute magnitude (a notion he had invented), then plotted a graph of these variables for a large number of stars. He noticed that the vast majority of stars fall along a thin, slightly s-shaped line from upper left (bright and blue) to lower right (faint and red). Because he published his results in a popular photography magazine, rather than in a scientific journal, astronomers didn't notice his result.

Almost a decade later, in 1914, the American astronomer Henry Norris Russell drew essentially the same graph, and made essentially the same discovery-that most stars fall near a thin line in the graph. Hertzsprung's article was noticed soon after that, and it was clear that both had independently discovered the spectrum-luminosity relationship.

For a time, this relationship was known in the United States only as the *Russell diagram*. But to a young Dutch astronomer, Willem J. Luyten, who had studied under Hertzsprung at Leiden University, the spectrum-luminosity relationship was always the *Hertzsprung diagram*. It was not until "many years later," according to Luyten, that another Danish astronomer, Bengt Stromgren, convinced other astronomers to acknowledge Hertzsprung as well. As Luyten wrote in his autobiography:

> *We now know that Russell had actually written to Hertzsprung and admitted that Hertzsprung had the idea first, adding, "When I publish, I shall mention this," but when actually publishing, he carefully forgot about it. Russell always resented my referring to the diagram as the Hertzsprung diagram. In any case, the truth eventually prevailed and it is now know as the H-R Diagram, with the order in which the names are cited in conformity with the chronological order of invention.*

What we now call the Hertzsprung-Russell diagram, or simply the *H-R diagram*, is one of the basic tools of modern astronomy.

Core Activity 9.2: Plotting an H-R Diagram

The Hertzsprung-Russell diagram is a graph that plots a star's absolute magnitude versus its temperature (spectral class). Below are a list of 25 of the brightest stars and a list of 25 of the nearest stars. Set up a graph of an H-R diagram with an appropriate scale and plot the 50 stars, using different symbols or colors to differentiate the two lists on the diagram. Then answer the questions about the stars that you have plotted.

Table 9.1

SOME OF THE BRIGHTEST STARS*

	Star	Spectral Class	Absolute Magnitude
1.	The Sun	G2	4.8
2.	Sirius (α CMa A)	A0	1.8
3.	Canopus (α Car)	A9	-5.5
4.	Vega (α Lyr)	A0	0.6
5.	Arcturus (α Boo)	K2	-0.1
6.	α Cen A	G2	4.5
7.	Rigel (β Ori)	B8	-6.7
8.	Capella (α AurA,B)	G6+G2	-0.3
9.	Achernar (α Eri)	B3	-2.8
10.	Procyon (α CMi A)	F5	2.7
11.	Agena (β Cen A,B)	B1	-5.5
12.	Acrux (α Cru A)	B0	-4.3
13.	Altair (α Aql)	A7	2.3
14.	Spica (α Vir)	B1	-3.6
15.	Aldebaran (α Tau A)	K5	-0.5
16.	Becrux (β Cru)	B0	-4.0
17.	Fomalhaut (α PsA)	A3	1.8
18.	α Cen B	K1	5.6
19.	Pollux (β Gem)	K0	1.2
20.	Regulus (α Leo A)	B7	-0.6
21.	Adhara (ε CMa A)	B2	-4.2
22.	Shaula (λ Sco)	B1	-5.1
23.	Bellatrix (γ Ori)	B2	-2.8
24.	Castor (α Gem A,B)	A2	0.6
25.	Alnath (β Tau)	B7	-1.4

* Absolute magnitudes of all stars except the Sun were calculated from parallax measurements and apparent magnitude (Hp) measurements taken from The European Space Agency, et al., *The Hipparcos and Tycho Catalogues* (17 Vols.), Noordwijk, The Netherlands: ESA Publications Division, 1997. ISBN 929092-399-7 (Vols. 1–17).

Table 9.2

SOME NEARBY STARS*

	Star	Spectral Class	Absolute Magnitude
1.	The Sun	G2	4.8
2.	α Cen C	M5	15.2
3.	α Cen A	G2	4.5
4.	α Cen B	K1	5.6
5.	Barnard's star	M5	13.2
6.	70 Oph A	K0	5.6
7.	Sirius A (α CMa A)	A0	1.8
8.	V1216 Sgr	M4	13.0
9.	ε Eri	K2	6.3
10.	HIP 114046	M0	9.8
11.	FI Vir	M4	13.4
12.	V1803 Cyg	K5	7.7
13.	Procyon (α CMi A)	F5	2.7
14.	61 Cyg B	K7	8.4
15.	HIP 91772	M3	12.3
16.	GX And	M1	10.4
17.	HIP 91768	M3	11.2
18.	ε Ind	K4	7.0
19.	τ Cet	G8	5.8
20.	YZ Cet	M4	14.1
21.	Luyten's star	M3	11.9
22.	Kapteyn's star	M1	11.0
23.	AX Mic	K7	8.8
24.	Kruger 60 A	M3	11.6
25.	V577 Mon	M4	12.9

* Absolute magnitudes of all stars except the Sun were calculated from parallax measurements and apparent magnitude (Hp) measurements taken from The European Space Agency, et al., *The Hipparcos and Tycho Catalogues* (17 Vols.), Noordwijk, The Netherlands: ESA Publications Division, 1997. ISBN 929092-399-7 (Vols. 1–17).

QUESTIONS ABOUT THE H-R DIAGRAM GRAPH:

1. Label the following branches of the H-R diagram: Main Sequence, Giant, Supergiant, White Dwarf. Calculate the percentage of stars that occupy each branch, and briefly describe, from the information on the two axes, the types of stars that occupy each branch.

2. Which stars are similar in magnitude and spectral class to the Sun?

3. Which list (brightest or nearest) gives the more typical example of the star population of the Milky Way Galaxy? Explain your reasoning.

4. Write a brief statement describing the relationship between absolute magnitude and stellar classification (temperature) of main sequence stars.

5. Does the above relationship hold for stars occupying the other branches of the H-R diagram?

6. Can you describe any relationships between absolute magnitude and stellar classification for any of the non-main sequence branches? Explain why you can or cannot.

7. Would you expect the same percentage of stars to occupy each branch of the diagram if all stars within the Milky Way Galaxy were plotted? Explain why or why not.

8. Why are there places on the diagram where no stars exist?

9. The next activity involves plotting variable stars on the same H-R diagram that you have constructed. Where do you think stars that vary in magnitude will end up on the diagram? Will they occupy one or more of the existing branches? Some of the empty places? Both? Write down your prediction, along with your reasoning. How would you plot a star that changes in brightness? What exactly is changing in these stars besides brightness?

Core Activity 9.3a: Variable Stars and the H-R Diagram

Plot the variable stars in Table 9.3a below. To see the relationship among main sequence stars, giants and white dwarfs to the variable stars, plot them on the same graph you made in 9.2. Variables have two absolute magnitudes, one at maximum and one at minimum. They also have enough variation to change spectral classes.

Table 9.3a

Star	Type*	Distance[1] (parsecs)	Magnitude[2] (apparent)	Spectral Class	Absolute Magnitude (M)
RT Aur	C	480	5.0–5.8	F4–G1	-3.4 / -2.6
delta Cep	C	300	3.5–4.4	F5-G1	-3.9 / -3.0
rho Cas	SR	3600	4.1–6.2	F8–K0	-8.7 / -6.6
T Cas	M	1700	7.9–11.9	M6–M9	-3.2 / +0.8
TU Cas	C	1100	6.9–8.2	F3–F5	-3.3 / -2.0
UU Aur	SR	560	7.8–10.0	C5–C7	-0.9 / +1.3
chi Cyg	M	106	5.2–13.4	S6–S10	+0.0/ +8.2
X Cyg	C	680	5.9–6.9	F7–G8	-3.3 / -2.3
T Cep	M	210	6.0–10.3	M5–M8	-0.6 / +3.7
Y Oph	C	880	5.9–6.4	F8–G3	-3.8 / -3.3
RS Boo	RR	1300	9.7–10.8	A7–F5	-0.9 / +0.2
VX Her	RR	2100	9.9–11.2	A4–F4	-1.7 / -0.4

*Variable star types (see page 152).

[1] Distances were calculated from parallax measurements taken from the European Space Agency, *et al.*, *The Hipparcos and Tycho Catalogues* (17 Vols.), Noordwijk, The Netherlands: ESA Publications Division, 1997. ISBN 92-9092-399-7 (Vols. 1–17).

[2] Apparent magnitudes taken from the 3rd and 4th editions of the *General Catalogue of Variable Stars*. Those of M-type variable stars are mean apparent magnitudes of maxima and minima.

1. Are the variables located on the H-R diagram where you expected them to be?
2. What are the differences?
3. The parallaxes of some of these variable stars are less than 0.001 arcsecond. The accuracy of the HIPPARCOS parallaxes is only 0.001 arcsecond, on average. How accurate will these absolute magnitudes be?

Core Activity 9.3b: Variable Stars and the H-R Diagram

Plot the variable stars in Table 9.3b below. To see the relationship among main sequence stars, giants, and white dwarfs to the variable stars, plot them on the same graph you made in 9.2. Variables have two apparent magnitudes, one at maximum and one at minimum. Use the distance modulus to calculate the absolute magnitudes from the apparent magnitudes. The parallax measurements have to be converted to parsecs. The distance in parsecs is the reciprocal of the parallax. They also have enough variation to change spectral classes.

Distance modulus: $M = m - 5\log_{10}(r/10)$

Table 9.3b

Star	Type*	Parallax[1]	Distance (parsecs)	Magnitude[2] (apparent)	Spectral Class	Absolute Magnitude (M)
RT Aur	C	0.00209		5.0–5.8	F4–G1	
delta Cep	C	0.00332		3.5–4.4	F5–G1	
rho Cas	SR	0.00028		4.1–6.2	F8–K0	
T Cas	M	0.00059		7.9–11.9	M6–M9	
TU Cas	C	0.00091		6.9–8.2	F3–F5	
UU Aur	SR	0.00180		7.8–10.0	C5–C7	
chi Cyg	M	0.00943		5.2–13.4	S6–S10	
X Cyg	C	0.00147		5.9–6.9	F7–G8	
T Cep	M	0.00476		6.0–10.3	M5–M8	
Y Oph	C	0.00114		5.9–6.4	F8–G3	
RS Boo	RR	0.00077		9.7–10.8	A7–F5	
VX Her	RR	0.00047		9.9–11.2	A4–F4	

*Variable star types (see page 152).

[1] Parallax measurements were taken from the European Space Agency, *et al.*, *The Hipparcos and Tycho Catalogues* (17 Vols.), Noordwijk, The Netherlands: ESA Publications Division, 1997. ISBN 92-9092-399-7 (Vols. 1–17).

[2] Apparent magnitudes taken from the 3rd and 4th editions of the *General Catalogue of Variable Stars*. Those of M-type variable stars are mean apparent magnitudes of maxima and minima.

1. Are the variables located on the H-R diagram where you expected them to be?

2. What are the differences?

3. The parallaxes of some of these variable stars are less than 0.001 arcsecond. The accuracy of the HIPPARCOS parallaxes is only 0.001 arcsecond, on average. How accurate will these absolute magnitudes be?

*Variable star types listed in the preceding tables:

C - Cepheid. These stars pulsate with periods of 1 to 70 days. Cepheids obey the period-luminosity relation.

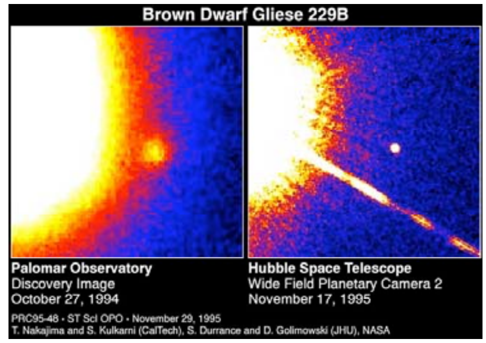
M - Mira. Red giant stars which pulsate with periods of 80 to 1000 days.

SR - Semiregular. These variables are giants and supergiants that show periodicity accompanied by intervals of irregular light variation. They have periods of 30 to 1000 days.

RR - RR Lyrae. Pulsating variable stars with periods of 0.05 to 1.2 days.

Planets or Stars?

There are two ways of detecting a planet, either directly by detecting radiation from the planet, or indirectly by observing the effect of the unseen planet on its parent star. Direct detection of planets is extremely difficult, as they are much dimmer than the stars they orbit. Direct observations have better results in the infrared band: peak emissions from planets occur in the infrared, and stars emit much less energy in the infrared band. Infrared imaging led to the discovery of the substellar brown dwarf Gliese 229B in orbit around the star Gliese 229.



Courtesy of Space Science telescope Institute/ NASA

The most common indirect methods track the motions of stars spectroscopically. If a star has a companion, then the star and companion orbit their shared center of mass, which causes perturbations, or disturbances, in the expected orbit of the star and/or Doppler shifts in spectral lines which can be detected.

The first planet found orbiting a Sun-like star is not at all what astronomers expected to find. The planet is orbiting 51 Pegasi, a 5.5-magnitude G-type star 40 light-years away, and very much like our Sun. The planet has half the mass of Jupiter with an orbital period of 4.2 days, so rapid that it must orbit at a distance of 7 million kilometers. Mercury orbits the Sun at a distance of 59 million kilometers. The existence of a giant planet so close to its star has created havoc with prevailing theories on the conditions necessary for planetary systems to form. The controversy surrounding 51 Pegasi and its companion is intense. However, the most recent evidence places the companion of 51 Pegasi in the planet category. The dividing line between brown dwarfs and planets is understood on a qualitative basis, but the actual dividing line between the two is unknown. A brown dwarf is by definition formed in the same manner as a star, and the dividing line between stars and brown dwarfs is mass. Brown dwarfs have an upper mass limit of around 75 to 80 Jupiters. However, the lower mass limit of brown dwarfs is not well understood. What is the amount of mass that represents the dividing line between brown dwarfs and planets? No one knows.

One likely planet is in a circular orbit approximately 2 AU's in radius around 47 Ursae Majoris. It is 75 million kilometers farther from 47 Ursae Majoris than Mars is from the Sun, and has a minimum mass of 2.3 Jupiters. One system which seems to be real was discovered by two radio astronomers. Two companion planets are orbiting a millisecond pulsar in Virgo named PSR 1257 + 12. The pulsar is 20 kilometers wide and 1600 light-years away. The inner planet orbits PSR 1257 + 12 at a distance slightly closer than Mercury and is 3.4 Earth masses, while the outer planet orbits slightly further than Mercury and is 2.8 Earth masses. 28 million kilometers separates the two planets; they are nearly twice as close to each other as Venus is to Earth. Since a pulsar has gone through a supernova explosion, any pre-existing planets would have been destroyed during the violent collapse. It is possible that a second generation of planets could have formed from the fierce wind of radiation from the pulsar. The wind would erode material from a companion star. Two millisecond pulsars have been caught in the act of vaporizing their companion stars, so PSR 1257 + 12 may have done the same. The planets would undoubtedly be hostile and barren.

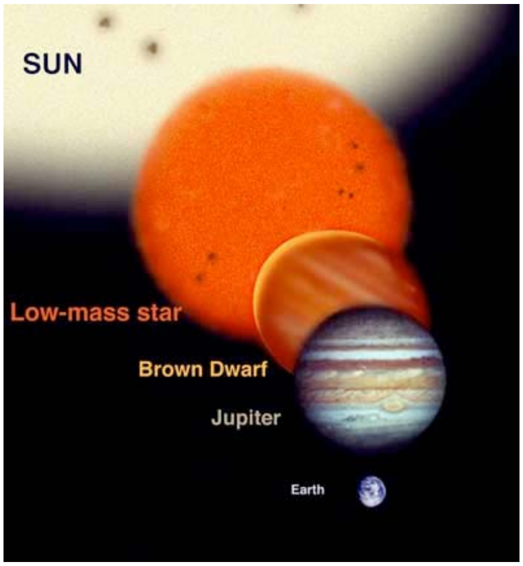
If other civilizations exist, they all share the same problems that the inhabitants of Earth face involving interplanetary or interstellar travel. One major obstacle is the mining of materials to support colonies on other planets or moons. The transportation of materials from the home planet would be cost-prohibitive and time-consuming. One possible solution being considered by NASA is the mining of basic materials from asteroids. Asteroids are being considered because of their variety of materials and favorable position for retrieval. Because of the long travel times to the main asteroid belt, the asteroids whose orbits bring them fairly close to Earth are being studied. The mining operations could dig and process the materials during the time spent traveling to the asteroid belt and back, and then the products could be recovered when the asteroid made its closest approach to Earth. The asteroid Apollo, for instance, crosses the orbit of Earth almost to Venus before returning to the asteroid belt. Apollo is one kilometer in diameter and has an orbit of 1.78 Earth years.

Combining information from spectral studies of asteroids and laboratory analyses of meteorites, investigations have indicated that near-Earth asteroids are rich in volatile materials such as water and organic materials, along with structural, precious, and strategic metals. The water could be decomposed into hydrogen and oxygen and used as rocket propellant. Samples in the form of carbonaceous chondrites and similar classes of meteorites which have impacted Earth indicate that their parent asteroids may have favorable mechanical properties. Some of these materials break up easily at very low pressures, much lower than that for most terrestrial materials. Some asteroid material can even be crushed by hand. Although other asteroids may be fundamentally tougher, impacts may have broken up their surfaces into thick layers of regolith (soil), and fractured the rocky material. This indicates that material from a near-Earth asteroid should be easily excavated and crushed by the same type of mechanical equipment already used for terrestrial mining.

A specific asteroid would have to be chosen before the mission could be planned. Physical properties of prospective candidates, such as mineral grades, mineral variability, specific mechanical characteristics of the asteroidal material, and orbital characteristics would have to be determined before a planned mission could proceed. The problems and expenses of a manned mission are huge. Such factors as long-term exposure to zero gravity, exposure to dangerous solar radiation, the design of controlled ecological life-support systems, and the deep-space transportation vehicle would all have to be considered. It is suspected that an asteroid mining mission will require human miners. Even on Earth many aspects of mining are not automated. Any type of automated or robotic asteroid mining project would have to work perfectly. Any small equipment failure would cause the entire mission to fail.

Although it might seem easier to move materials in zero gravity than on Earth, inertia, as well as the lack of gravity and weightlessness, are major problems to consider. One problem is that of holding mining and excavation tools to the surface of an asteroid. On Earth, equipment is held down solely by gravity.The property of inertia, Newton's second law, states that all objects remain at rest on in a constant straight-line motion unless a force is applied. This results in the problem of containing the excavated material, both the large and the small fragments. Rock-fracturing places an initial velocity on the broken material. On Earth, gravity quickly collects the broken rock. In weightlessness, the property of inertia would cause the broken rock to behave like out-of-control billiard balls, a potentially destructive game. The fine particles generated by rock-fracturing would obscure vision and clog equipment. Even though lunar mining would be cheaper and easier, the rich variety of materials in asteroids keeps them on the list of possible future mining sites.

SPACE TALK



More than 80% of all nearby stars are **red dwarfs**. Red dwarfs lie at the lower right- hand corner of the **H-R diagram**. These red, cool stars have a mass of one-half to one- tenth the mass of the Sun and are so cool that their **effective temperature** of ~2500K can be achieved in blast furnaces here on Earth. Larger main sequence stars like the Sun have different zones running from the core to the **photosphere**, or "surface." Surrounding the core is a **radiative zone** which carries the energy from the fusion process towards the surface; this zone is itself surrounded by a **convective zone** where the gases rise and fall like a boiling pot of water. Red dwarfs have no radiative zone; these stars are so cool that the entire interior is convective. If the Sun is thought of as being at full boil, a red dwarf would be at a gentle simmer.

Several years ago astronomers predicted the existence of another stellar-like object called a **brown dwarf**. Brown dwarfs are about the size of Jupiter, only 10 to 80 times more massive, up to about 8% of the Sun's mass. These objects flicker on and off by "burning" deuterium (heavy hydrogen) or other light elements; however, they are incapable of converting normal hydrogen into helium in sufficient quantities to shine steadily. Since brown dwarfs are not massive enough to have high enough temperatures and pressures in their cores to sustain a steady rate of fusion, they gradually fade throughout their lives. Their effective temperatures are thought to be ~740K. Brown dwarfs would also have fully convective interiors, but not with consistency—sort of an intermittent simmer. For galaxies, clusters, and superclusters to remain gravitationally bound and not fly apart, an adequate amount of mass is required. It is calculated that approximately 90% of the mass in the galaxy is not observable from Earth; all the objects we see constitute only ~10% of the required mass. Since the majority of main-sequence stars are dim red dwarfs, it is thought that enormous numbers of even dimmer brown dwarfs must exist, and some astronomers think that these brown dwarfs are significant contributors to the "missing mass" problem.

30 Brown Dwarfs in Pleiades (Spitzer)

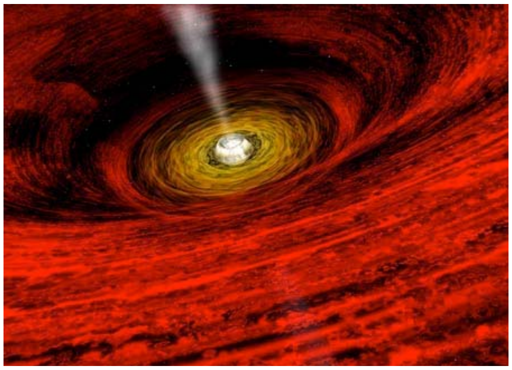
The first confirmed brown dwarf was discovered in 1995. Gliese 229B, which orbits a small spectral class M red star 19 light-years away in the direction of Canis Major. The search for brown dwarfs is difficult. It is hard to find objects with luminosities that are too dim, temperatures too cool, or colors too red for hydrogen-burning stars. Brown dwarfs also continually fade, and their luminosities, temperatures, and colors constantly change over time. To know if a candidate is actually a brown dwarf, either the age or the mass would have to be known. If a dim object has less than 7 to 8 percent of the Sun's mass, it cannot possibly be a star. Recent advances in technology have resulted in a growing catalog of brown dwarfs. The Spitzer infrared observatory has imaged several brown dwarfs in the Pleiades open cluster, a swarm of brown dwarfs has been imaged in the Orion Nebula, and even a binary system with two young brown dwarfs with masses of 50 and 25 times the mass of Jupiter have been detected orbiting each other at a distance of about 20 billion miles.

The mass of stars is difficult to determine. Mass can be directly measured only by applying Kepler's third law of planetary motion to stars in multiple star systems. A new method has been developed using **spectroscopy** and the element lithium. In normal stars, lithium is destroyed in nuclear collisions. Red dwarfs are fully convective and the lithium gets carried to the center and destroyed. Objects cooler than red dwarfs do not have a sufficiently high temperature to destroy lithium, so it becomes part of the atmosphere and can be detected by spectroscopic analysis. Gliese 229B has an absolute magnitude of ~+15.5, and therefore probably has a mass below the required 8% of the Sun's mass. The near-infrared spectrum shows the same molecules which exist in the clouds around Jupiter. This limits the effective temperature to less than 1000K, too low for a star. However, Gliese 229B is too close to its companion for a high-precision measurement of its mass, though new instruments being developed for HST might be able to handle the measurement. It is also too faint and too close to its brighter, primary star to apply Kepler's law or to determine the existence of lithium in its spectrum.

Brown dwarfs are not on the H-R diagram because they are not true stars and have no spectral classification. Main sequence stars similar to our Sun will evolve into red giants, sometimes throwing off planetary nebulae, and will eventually become white dwarfs. Stars in these two stages, red giants and white dwarfs, are located on the diagram because they have specific relationships between absolute magnitude and temperature (spectral types). The white dwarf stage will last for billions of years until these cores finish radiating away their energy and become cold chunks of carbon. The Sun will become a red giant in about five billion years, eventually becoming a white dwarf the size of the Earth. Larger stars which enter the red supergiant stage will go through a supernova explosion. The two end products of this explosion, **neutron stars** and **black holes**, are also not on the H-R diagram.

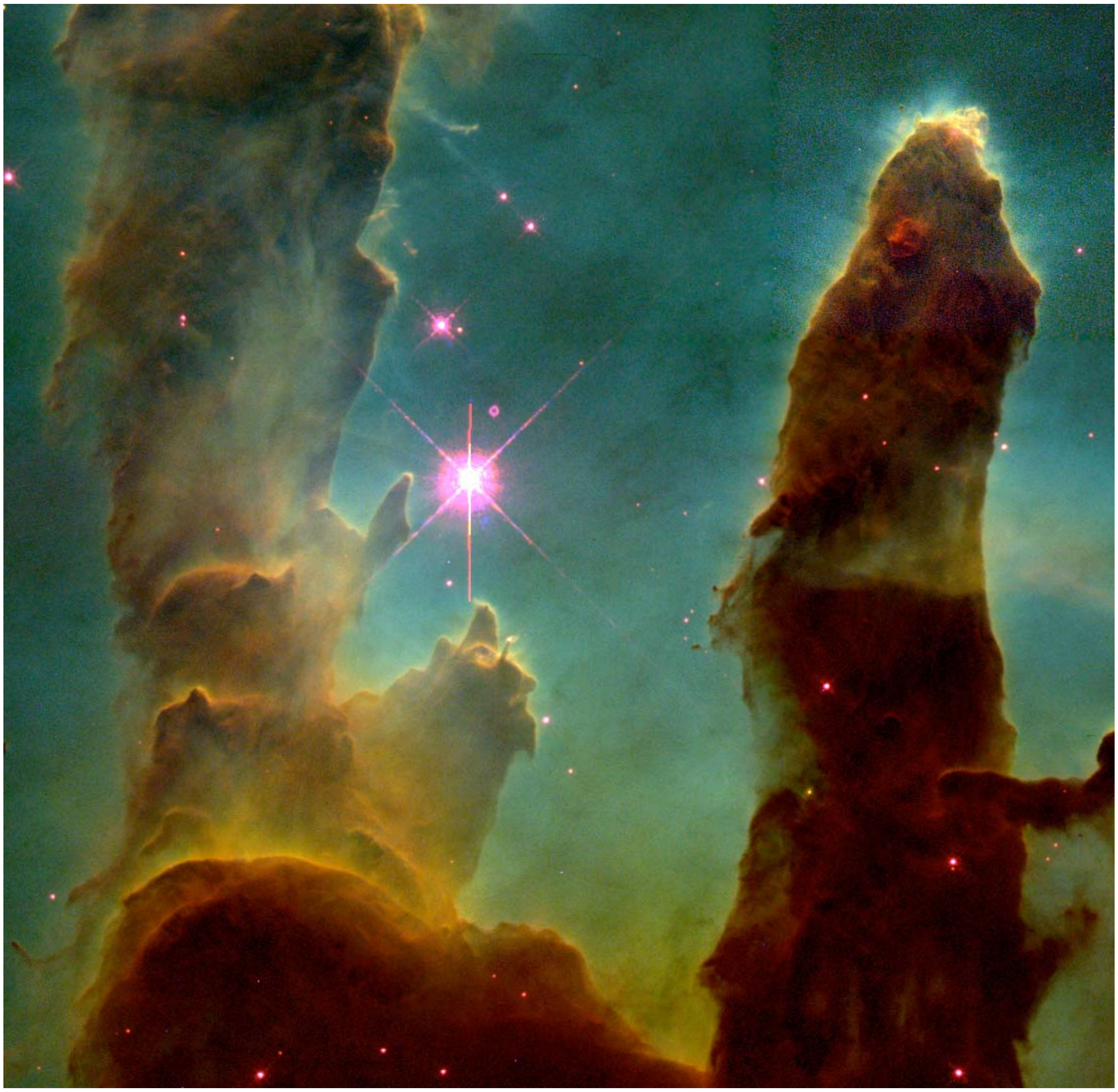
In white dwarfs, electron clouds are in contact with each other. The white dwarf does not collapse any further because its mass is not sufficient to overcome the repulsive force of the electron clouds. The white dwarf is then held in equilibrium by the opposing forces of **electron degeneracy pressure** and gravity. More massive stars can overcome the resistance of the electrons. During the collapse of these stars, the electrons are driven into the nuclei where they combine with protons and become neutrons. Neutrons are in contact with neutrons, and are held apart by the strong nuclear force—the strongest known force in the universe. Now the core is held in equilibrium by the opposing forces of **neutron degeneracy pressure** and gravity. The core can collapse no further and becomes a neutron star. A neutron star is so dense that a pinhead of its matter weighs more than a million tons. Some of these collapsed stars rotate and are called **pulsars**;

some of them, called millisecond pulsars, complete one cycle in just a few thousandths of a second.



Black Hole Illustration, April Hobart

In the most massive stars, even the strongest known force cannot withstand the force of gravity. Neutrons are pushed into neutrons, and nothing can stop the complete and total collapse of the star. It continues falling into itself until it becomes a **singularity**, a point of zero radius. The star becomes so dense, and the gravitational field so strong, that even light cannot escape. Black holes may cease to exist in the visible universe, but they leave behind clues to their existence. Such a large amount of matter confined in such a small space severely distorts the surrounding spacetime and any companion stars. Despite being the weakest of the four forces of nature, gravity overcomes the strongest forces, and defeats them all in a massive collapsing star.



1995 Hubble photo of the Eagle Nebula. The pillars are actually columns of cool interstellar hydrogen gas and dust that serve as incubators for new stars.

Chapter 9: The Life of a Star

Summary

Through spectroscopy, the analysis of starlight, we can determine the chemical composition and temperatures of stars and then classify them by spectral type. If the absolute magnitude is also known, stars can be plotted on a graph of spectral type versus absolute magnitude known as the Hertzsprung-Russell (H-R) diagram. The H-R diagram represents the evolutionary stages of stars, providing us with information on the current status of the thermonuclear fusion process in the stellar core.

Terminology

black body	electron degeneracy pressure	pulsars
black body radiation	H–R diagram	radiative zone
black holes	luminosity	red dwarf
brown dwarf	main sequence	singularity
convective zone	neutron degeneracy pressure	spectrophotometer
distance modulus	neutron star	spectroscopy
effective temperature	photosphere	Stefan-Boltzman's Law
	Planck's Law	Wien's Law

Common Misconceptions

1. *Each star's chemical composition varies greatly from that of other stars.*
2. *All stars eventually become black holes.*

SUGGESTIONS FOR THE POSTER PAGES, INVESTIGATIONS, AND ACTIVITIES

Investigation 9.1: The Continuous Spectrum

For this activity you need to project a spectrum onto a piece of paper attached to a wall or board. Cut out a piece of sturdy cardboard the size of a 35mm slide that will fit into a slide projector. Cut a slit into the middle of the cardboard with a razor blade, approximately one inch long and 1/8th inch wide. Insert the cardboard into the slide projector so that the slit is vertically oriented. Tape a diffraction grating to the lens of the projector. The room has to be extremely dark. Turn the projector on and a continuous spectrum will appear on the paper or board.

Poster Page: "The Most Original Thinker of All..." (Antonia Maury)

There are many uses for spectral analysis besides determining the composition and temperature of stars. Students tend to think that something like spectroscopy is not really relevant to them because they are never introduced to these other uses.

Why did Hertzsprung publish his results in a popular photography magazine? Did he lack credibility in the professional scientific community because of his amateur status? Would he have known how to approach a more technical journal to publish his article? Would they have published the article of an amateur? History is full of examples of people whose work was unknown or unacknowledged for years. Sometimes others took credit for these people's work. Would this same problem exist today? Is it still possible for important results to go unrecognized? How would you go about communicating a new scientific relationship or development?

Core Activity 9.2: Plotting an H-R Diagram

If you are interested in having students study stellar spectra, you should consider the CLEA software. One CLEA program addresses stellar spectra. This astronomy software is free, and includes student manuals and activities. The original software is made for PCs; however, most programs are now available in Macintosh format. It can be downloaded from the internet or sent to you by mail. The address is included in the Resource List. RESOURCE

A completed plot of this activity is included. Students should realize that neither plot will give an accurate picture of the average distribution of stellar types. However, the plot of both some of the brightest and some of the closest stars should have the same type of distribution that would be observed from any spot in the galaxy, since there is no preferred viewpoint. We would see approximately the same spectral types in the same amounts from any other planet within the disc of the galaxy. (See completed plot on opposite page.)

Before the students plot the variable stars in the next activity, have them discuss where they think these stars might be located on the H-R diagram.

Core Activity 9.3a and 9.3b: Variable Stars and the H-R Diagram

Variable stars are also on the H-R plot. The students should realize that they will have to plot two points for each star, one for maximum and one for minimum. Since these stars vary between these two points, a bar should connect the points. Variables are also classified according to spectral types, although the same star might range from one spectral class to another. Variable stars can occupy different places on the H-R diagram: some are main sequence stars, and others belong to the giant branch. A few range outside of a particular band. The students should label the variable star plot lines with the type of variable (see completed plot on following page).

We have included two different versions of this activity. In Core Activity 9. 3a, the absolute magnitudes and distances in parsecs have been calculated, so the students plot only the information. The second version, 9.3b, contains the parallax measurements, which have to be converted to parsecs by taking the reciprocal of the parallax. Also, the absolute magnitudes are not given, only the apparent magnitudes. The apparent magnitudes can be converted to absolute magnitudes by having the students use the distance modulus.

EXAMPLE. Use the distance modulus equation to calculate the absolute magnitude for delta Cep.

Since delta Cep is a variable star, the absolute magnitude at maximum will be brighter than the absolute magnitude at minimum. We will calculate both maximum and minimum values to find the range of absolute magnitude for delta Cep.

From Table 9.3b, for delta Cep, $m = 3.5 – 4.4$ and $\pi = 0.00332''$

Distance Modulus equation: $M = m – 5 \log_{10} (r/10)$

A. Calculate the absolute magnitude of delta Cep at maximum:
   1. Find r from the parallax: $r = 1/ \pi = 1/0.00332 = 301.2048$
   2. $M = +3.5 – 5 \log_{10} (301.2048/10)$
   3. $M = +3.5 – 5 \log_{10} (30.1205)$
   4. $M = +3.5 – 5 (+1.4789)$
   5. $M = +3.5 – (+7.3945)$
   6. $M = +3.5 – 7.3945$
   7. $M = –3.89$
   8. M rounds off to –3.9 for delta Cep at maximum
B. Calculate the absolute magnitude of delta Cep at minimum:
   1. Find r from the parallax: $r = 1/ \pi = 1/0.00332 = 301.2048$
   2. $M = +4.4 – 5 \log10 (301.2048/10)$
   3. $M = +4.4 – 5 \log10 (30.1205)$
   4. $M = +4.4 – 5 (+1.4789)$
   5. $M = +4.4 – (+7.3945)$
   6. $M = +4.4 – 7.3945$
   7. $M = –2.99$
   8. M rounds off to –3.0 for delta Cep at minimum

Thus, the absolute magnitude range for delta Cep = –3.9 to –3.0. (Remember, the larger the negative magnitude, the brighter is the star.)

Once the students have plotted the variable stars on the H-R diagram, have them look up the different types of variable stars in the VSTAR database and see what their light curves look like. They will see that different kinds of variable stars have particular patterns. Before they use VSTAR, have them discuss the behaviors of the variables and what differences the curves may have.

VSTAR

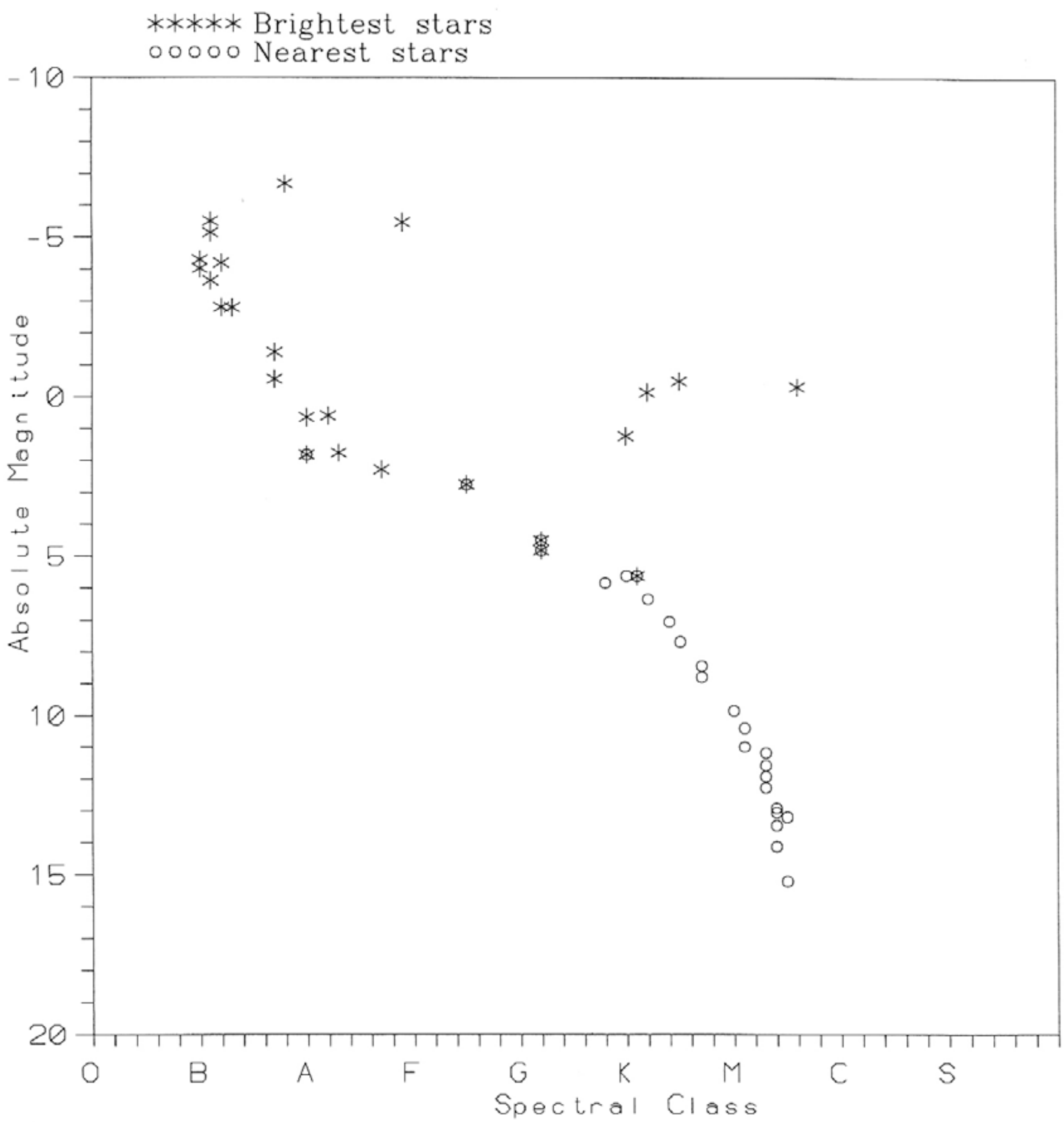
NOTE: There is a problem with the absolute magnitude values of the last two stars in Table 9.3a, RS Boo and VX Her. These two stars are not really as bright as they appear to be from the values given here; they are in fact always fainter than magnitude 0.0, with mean absolute magnitudes of +0.6 to +0.9. The falsely bright values which are given are derived from the HIPPARCOS measurements, and result from the fact that the accuracy of HIPPARCOS measurements is 0.001 arcsecond, and the parallaxes of some of the variables, including RS Boo and VX Her, are less than 0.001 arcsecond. The parallax measurements are therefore highly questionable, and at the limit of precise measurement an extremely small parallax measurement error will produce very large distance and absolute magnitude errors. The falsely bright absolute magnitude values are included in the table to keep the source of the absolute magnitude data consistent.

Poster Page: Planets or Stars?

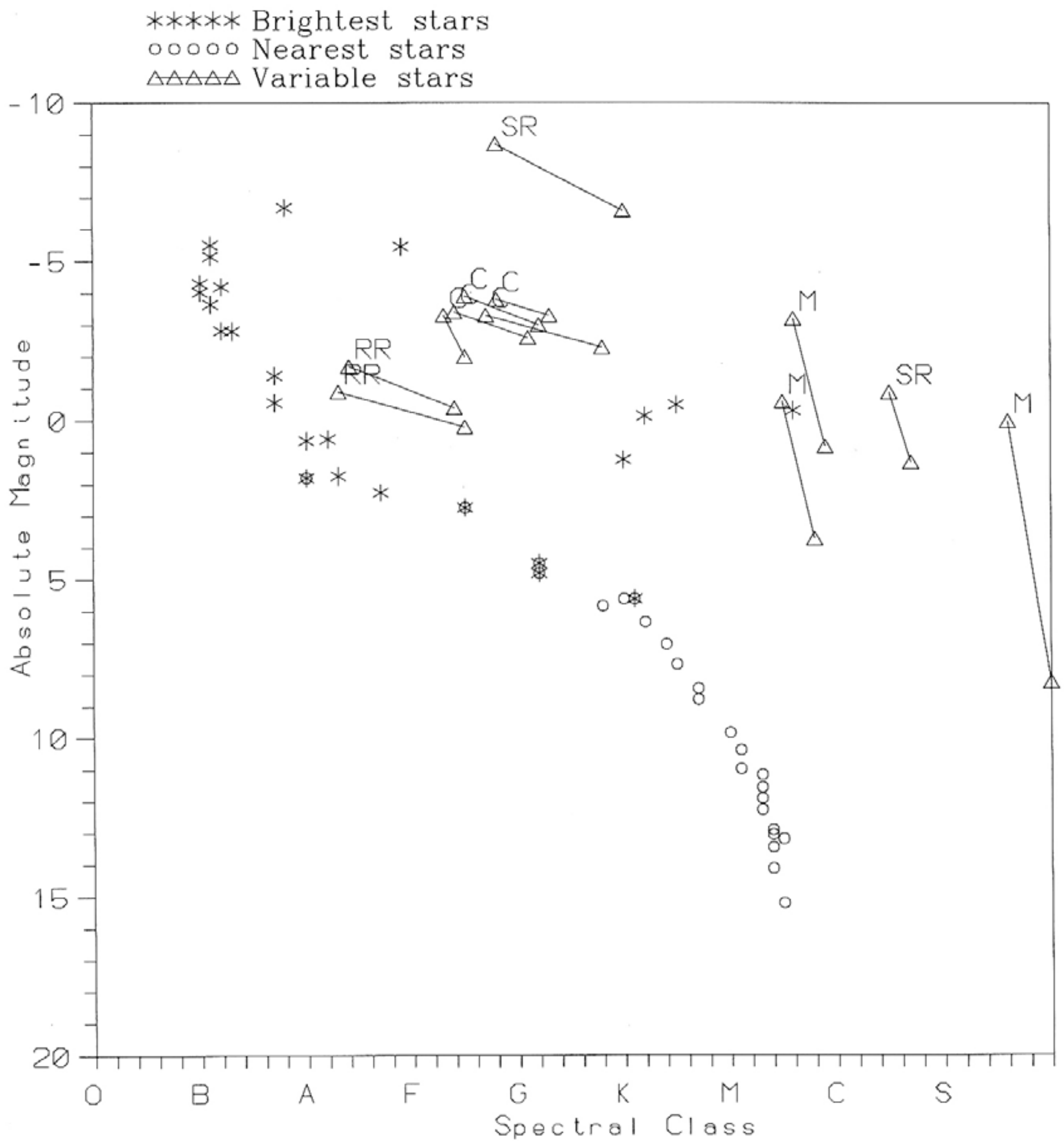
The search for other planetary systems is similar to the search for other life-forms and for other planets which have the capability for the origin and evolution of life. Any search of this nature requires space travel either by astronauts or robots. It is a serious mission to research the possibilities of space stations, space ships, and the mining of planetary materials that would sustain further space travel. NASA has given it much consideration and conducted several feasibility studies on all aspects of extraterrestrial travel. The Biosphere outside Tucson, Arizona, is a privately-sponsored experiment in completely contained and self-reliant life. This type of living environment is necessary for the habitation of other planets. When considering the colonization of other planets, how does one take into account the gravity, radiation levels, varying types of atmospheres, and absence of necessary materials? Because of the unique aspects of each planet, different types of space colonies would be necessary for the Moon, Mars, Titan, and other yet-tobe discovered planets. In what ways would they be different? Why? This topic is potentially rich in interdisciplinary connections and research projects. NASA has a publication series entitled *Space Resources,* which describes the results of their studies on possible future projects involving non-terrestrial activities. (See Resource List for details.)

RESOURCE

Completed H–R Plot for Core Activity 9.2



Completed H–R Plot for Core Activities 9.2 and 9.3



Chapter 10: Statistical Concepts

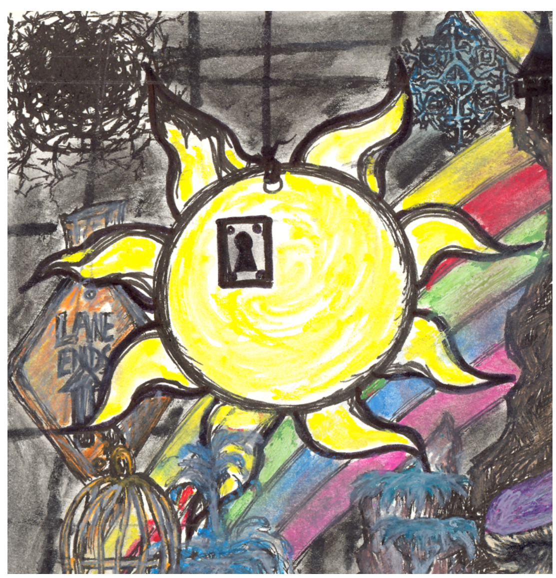
Introduction

Miranda Read, artist

As you gain experience in observing variable stars, your accuracy in estimating magnitudes will increase. Nonetheless, there will always be some scatter in your data. Doing *real* science and gathering *real* data always result in measurements that have inconsistencies. Science is a process of searching for answers that are as yet unknown. Therefore we cannot strive for "correctness." Scientists aim for precision—exactness in procedure and measurement—so that their results, whatever they may be, will be as accurate as possible. You will already have noticed in preceding activities that even when several individuals are measuring the same objects with the same measuring tool—be it string, a ruler, or the human eye—no one arrives at the exact same result. There is no way to avoid scattered data, no way to avoid the inconsistencies that come from random error. However, there are ways of eliminating the most extreme scatter so that your data are still accurate enough to be useful.

The world of science is one of continuous discovery. The excitement of discovery is in *not* knowing the correct answer before you start, and—most of the time, anyway—not knowing the *exact* answer after you finish. In most areas of science, making observations is but a tiny part of the discovery process. The bulk of the effort goes into extracting and analyzing meaningful information from observational data.

When dealing with quantitative data, *statistics* is the ideal mathematical tool to allow you to express the validity of your data, to view them from different perspectives, and evaluate their precision and quality. The following examples will help to explain fundamental statistical concepts, some of which you may already know.



Miranda Read, artist

Investigation 10.1: Finding the Average

1. Make the following two sets of measurements: the height and the arm length, in centimeters, of all the people in your classroom. For each person in the class, take three separate measurements of their height and their arm length and take the two averages. Did you all get the same arm length and height for each individual in the class? If you worked individually or in small groups, discuss with your classmates the procedures you used to take the measurements and calculate the averages. Discuss the differences in measuring techniques.

2. Obtain the average of the measurements taken for your height and arm length (in centimeters) from all of your classmates and enter them in Table 10.1. Compare the measurements. Are the measurements close together or far apart? How large is the scatter? What are some of the possible sources of random and/or systematic error which could have contributed to the differences in the results of the measurements?

3. Calculate the classroom average for your height by adding all the measurements in Table 10.1 together and dividing by the total number of measurements. Repeat the same calculation for arm length. Enter these two values, along with your name on line 1, in Table 10.2. Enter the calculated averages and names for the rest of the class. Add the measurements for heights and divide by the total number of measurements. You now have the average height for the entire class. Repeat the procedure to determine the average arm length for the class.

Table 10.1: Individual Averages

Name:		
Measurement from classmate:	Height (cm)	Arm Length (cm)
#1		
#2		
#3		
#4		
#5		
#6		
#7		
#8		
#9		
#10		
#11		
#12		
#13		
#14		
#15		
#16		
#17		
#18		
#19		
#20		
#21		
#22		
#23		
#24		
#25		
AVERAGES:		

Table 10.2: Classroom Averages

Names:	Height (cm)	Arm Length (cm)
#1		
#2		
#3		
#4		
#5		
#6		
#7		
#8		
#9		
#10		
#11		
#12		
#13		
#14		
#15		
#16		
#17		
#18		
#19		
#20		
#21		
#22		
#23		
#24		
#25		
AVERAGES:		

Core Activity 10.2: Constructing a Histogram

The *histogram* is one of the most important tools of elementary statistics. The histogram is a graph illustrating how likely it is to find any particular result in a set of data. In appearance, a histogram is similar to a bar graph. We begin by taking all possible results, and dividing them into ranges called *bins*. Then we count how many of the data points fall into each range. Finally, we divide each count by the total number of data points, to give us the *relative frequency*. Relative frequency is an estimate of the *probability* that any given data point will fall within this range. This method of graphically representing data is a powerful tool for analyzing a set of data (see Figure 10.1 below).

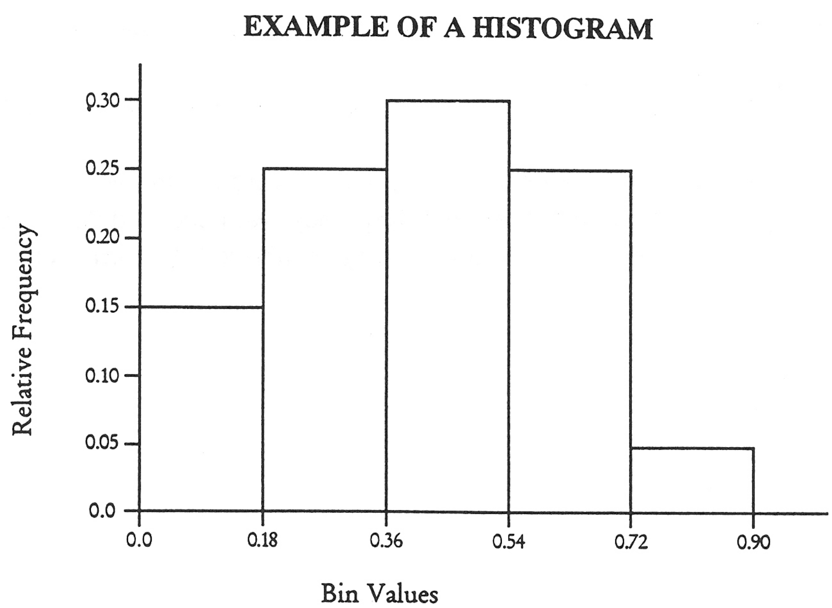


Figure 10.1

Constructing a histogram will allow you to visually examine the distribution and scatter of your data points. It is a quick way to assess the precision of a set of data and decide if the distribution of data is typical. You will be able to determine if the scatter of the data set is large or small, and how precise the measurements were. To construct a histogram, a data set has to be divided into equal groups, or bins. It will require some thought as to how a set of numbers should be divided into bins. To help make this decision, use the following rules:

a. Each bin has to be of equal value.

b. Each number falls into one and only one bin.

c. No number falls on the boundary or “in between” a bin.

d. At least 5 bins are necessary for a good representation of the data.

EXAMPLE:

Consider the following set of twenty numbers:

0.3, 0.5, 0.7, 0.6, 0.3, 0.5, 0.4, 0.1, 0.6, 0.1, 0.2, 0.8, 0.4, 0.7, 0.6, 0.3, 0.4, 0.5, 0.2, 0.5

The smallest number is 0.1 and the largest is 0.8. We need to arrange these numbers into at least five equal bins, and each of the numbers has to fall into a bin. A simple way to have equal bin values would be to center the first bin over the value of 0.1 and the last bin over the value 0.8. This ensures that all the numbers will fall into a bin and not on the boundaries between any of the bins. Therefore the value of each bin would range from .05 less than each number to .05 more than each number. If the first bin is centered on .1, the bin value would be .05 to .15. So we will have 8 bins which have values of:

[.05–.15], [.15–.25], [.25–.35], [.35–.45], [.45–.55], [.55–.65], [.65–.75], [.75–.85]

These bin values will be on the horizontal axis of our histogram. On the vertical axis is the relative frequency. To determine the relative frequency, we need to determine, by counting, how many of the data points in our set of numbers above falls into each bin.

Bin 1 [.05–.15] – 2

Bin 2 [.15–.25] – 2

Bin 3 [.25–.35] – 3

Bin 4 [.35–.45] – 3

Bin 5 [.45–.55] – 4

Bin 6 [.55–.65] – 3

Bin 7 [.65–.75] – 2

Bin 8 [.75–.85] – 1

total: 20

To determine the relative frequency with which each number occurs, the number of data points that falls into each bin is divided by the total number of data points; that is, the frequency of numbers which fall into Bin 1 is equal to 2 (0.1 occurs twice in the data set) divided by 20, or 0.1. For our 8 bin values above the relative frequencies are:

Bin 1: 2 divided by 20 = 0.10

Bin 2: 2 divided by 20 = 0.10

Bin 3: 3 divided by 20 = 0.15

Bin 4: 3 divided by 20 = 0.15

Bin 5: 4 divided by 20 = 0.20

Bin 6: 3 divided by 20 = 0.15

Bin 7: 2 divided by 20 = 0.10

Bin 8: 1 divided by 20 = 0.05

total: 1.00

Notice that the relative frequencies all add up to 1. This is because of the definition of relative frequency. It is the bin count, divided by the sum total of all the counts. So the sum of the relative frequencies is the sum of the counts, divided by the sum of the counts—which of course equals 1.

The relative frequencies and bin values can now be used to construct the histogram below.

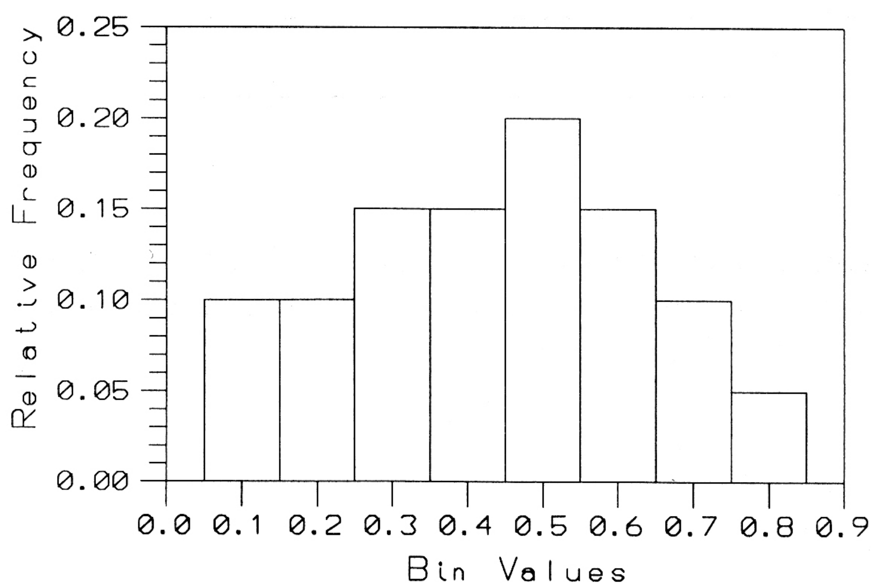


Figure 10.2

1. Using all of your height measurements from your classmates in Table 10.1, determine an appropriate number of bins, and the bin values. Enter the bin values in Table 10.3. Calculate the relative frequency of each measurement and enter it in Table 10.3. Use the information in Table 10.3 to construct a histogram.

Table 10.3

Bin Value	# of Data Points	Relative Frequency
TOTALS:		

2. On your histogram, mark the midpoint of the top of each bar (bin value) with a dot, and connect the dots with a smooth curve, as in the example histogram (Figure 10.3) on the following page.

EXAMPLE OF A HISTOGRAM

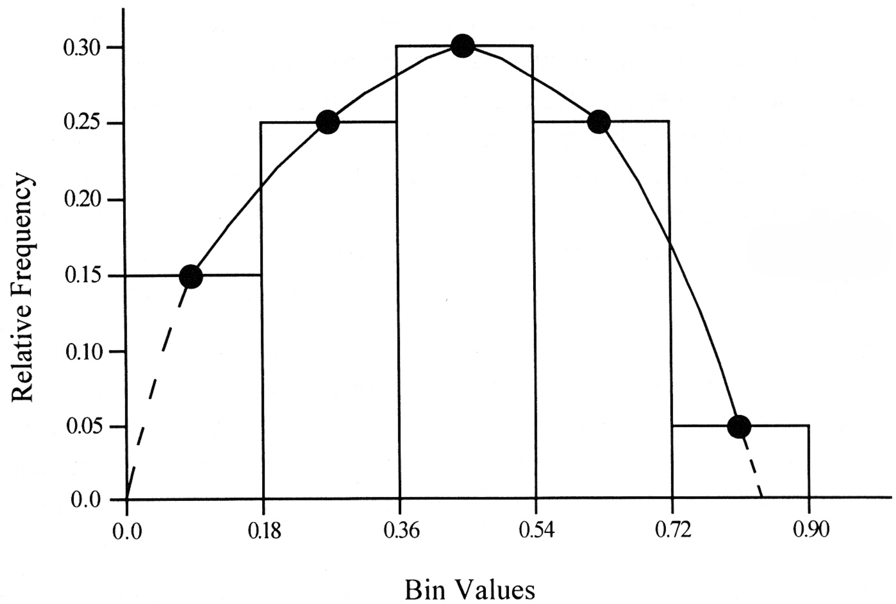


Figure 10.3

3. You now have a visual summary of your data. The resulting curve should be reasonably close to a symmetrical bell-shape. This is referred to as a normal curve, meaning that your data set follows a normal distribution and your measurements are reasonably precise. (There is an extended explanation of the normal curve on page 172 of this chapter.) Discuss possible factors which might have contributed to the amount of scatter.

Core Activity 10.3: Finding the Average Deviation

1. In Chapter 6 you compiled a set of magnitude estimates for Variable Star X in Table 6.6. You can now use this data set for statistical analysis. (If your class has collected a sufficient number of actual variable star observations, you may use those data instead.) Using either the information on Star X from Table 6.6 or your classroom observational data, transfer the data to columns [A] and [B] in Table 10.4. Then complete columns [C] and [D] using the data from Table 6.6. You are entering the JD, your magnitude estimation, the number of classroom estimates, and the class averages of the estimations for Star X. You will need to calculate the class average for each Julian Date.

2. The next column [E] in Table 10.4 is labeled "*Range.*" The range is simply the difference between the smallest and largest value in a set of data. Refer back to Table 6.6, which lists the estimates of the magnitude of Star X for the entire class. For each JD, look at the estimates in the row; find the smallest and largest values and take the difference between the two values. Enter the result in column [E].

3. You are now ready to calculate the class average deviation by using the Star X information in columns [B] and [D] from Table 10.4.

    a. For the first JD magnitude estimation, determine the difference of your observation from the class average and take the absolute value. This is your individual deviation. (You will use these numbers again in Core Activity 10.4.)

    b. Add together the individual deviations for the entire class for the first JD estimation, and divide the sum by the number of observations. This is the average deviation. Enter the result into column [F] in Table 10.4.

    c. Repeat for all the remaining magnitude estimates.

Determining the range gives you an idea of the amount of variability or scatter in the values within the data set. The range gives a general idea of the variation; there are other methods of analyzing the data that are more "*sensitive*" than the range—that is, they give a more detailed look at how much each data point deviates from the average. The most basic method of expressing the spread of the data in quantitative terms is called the *average deviation*.

Table 10.4

Name of Variable Star:								
Data point	[A] Julian Date	[B] Magnitude of Star (your estimate)	[C] # of class obser-vations	[D] Class Average	[E] Range	[F] Average Deviation	[G] Standard Deviation	[H] Standard Error of Average
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								
16								
17								
18								

	Table 10.5 **Two Hypothetical Data Sets**	
	Sample 1	**Sample 2**
Measurements	1, 2, 3, 4, 5	2, 3, 3, 3, 4
Dot Diagram (showing frequency distribution)	* * * * * 1 2 3 4 5	* * * * * 1 2 3 4 5
Average	$\frac{1+2+3+4+5}{5}$ $= \frac{15}{5} = 3$	$\frac{2+3+3+3+4}{5}$ $= \frac{15}{5} = 3$
Distance of Measurement from Average or Deviation from Average	(1-3), (2-3), (3-3), (4-3), (5-3) or -2, -1, 0, 1, 2	(2-3), (3-3), (3-3), (3-3), (4-3) or -1, 0, 0, 0, 1

Study the two hypothetical data sets in Table 10.5 above. The first row shows the frequency distribution of each data point, the second shows the calculated average, and the third row shows the calculations for determining the distance each data point is from the average. This number is calculated by subtracting the average from each number. The distance from the average is called the *deviation* from the average.

To calculate the average deviation, drop the negative signs from the third row above. Use the absolute value of the numbers (they are all treated as though they are positive). Then the absolute values of each number are added together, and the sum is divided by the number of data points.

For Sample 1 above:

$$\frac{2+1+0+1+2}{5} = \frac{6}{5} = 1.2$$

For Sample 2 above:

$$\frac{1+0+0+0+1}{5} = \frac{2}{5} = 0.4$$

Now relate these results to the dot diagram showing frequency distribution in Table 10.5 on the previous page. Sample 1 has an average deviation of 1.2, showing that there is a larger spread in the data set than there is in Sample 2, which has a lower average deviation of 0.4. Sample 2, with a lower average deviation, must have less variation or scatter in the data: all of the data are close to the average. Conversely, Sample 1 has a larger range and the data are not as closely centered to the average.

In summary, to calculate the average deviation:

1. Calculate the average of the data set.
2. Subtract the average from each data point to get the difference.
3. Take the absolute value of each difference.
4. Add the absolute values together.
5. Divide the sum of the absolute values by the number of data points.

In mathematical terms, the process described above is represented by the following:

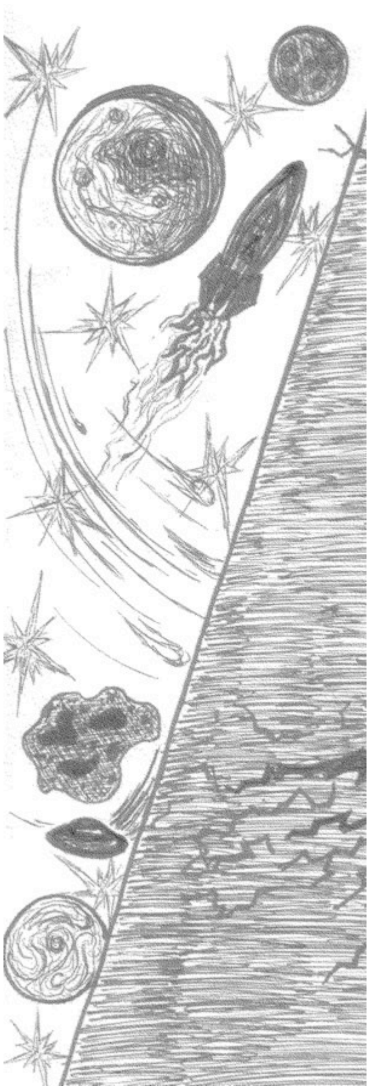
$$\frac{\Sigma \left| x_i - \bar{x} \right|}{n}$$

where	x_i	=	the value of each data point
	$\bar{x}$	=	the average of all the data points
	Σ	=	the Greek letter sigma, meaning "sum of"
	n	=	the total number of data points
	$\vert\ \vert$	=	the "absolute value of"

You will calculate the Standard Deviation [G] for Table 10.4 in Core Activity 10.4 and the Standard Error of the Average [H] in Core Activity 10.5.

Hands-On Universe

Hands-On Universe (HOU) is a program that enables high school students to request their own observations from professional observatories. HOU students download Charge Coupled Device (CCD) images to their classroom computers and use HOU's powerful image processing software to visualize and analyze their data. The HOU program collaborates with telescopes in Hawaii, Illinois, California, Washington, Sweden, and Australia to form a network of automated telescopes for educational use. Student requests are processed by the network to decide which telescope is best suited for the particular request, considering weather, geography, scheduling, and equipment. The network provides fast turn-around for student requests and allows real-time observing in certain cases because of the location of the telescope in various time zones. A key component of the HOU project is student research and investigation. Many students have used HOU to explore astronomical phenomena and have written web-based reports of their work.



Miranda Read, artist

Cerro Tololo Observatory in Chile

Students have a chance to work with scientists on original research projects, such as the HOU Asteroid Search. The asteroid search uses images from the Berkeley Cosmology Project, which is composed of a team of scientists searching for very distant supernovae. They use world-class telescopes such as the Cerro Tololo International Observatory (CTIO) in Chile to search for type Ia supernovae near the edge of the visible universe. The scientists share their data with HOU classes so that students can search for very faint asteroids in the same regions of the sky. To date, five previously unknown asteroids have been recorded by HOU students.

The HOU website is: http://hou.lbl.gov

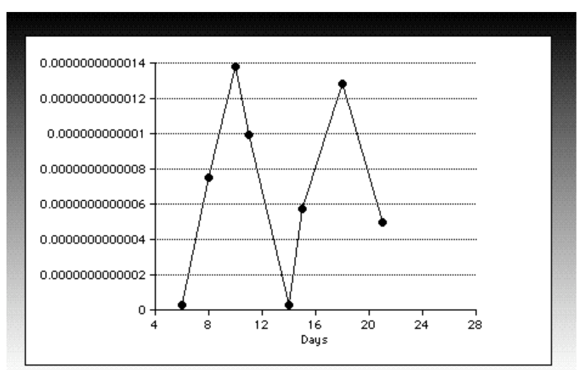
Hands-On Universe classes are involved with several research projects, including searching for supernovae and asteroids, creating H-R diagrams from images of open star clusters, and performing photometric measurements of Cepheid variable stars. One HOU project report is summarized below. *(used with permission from Hands-On Universe, Lawrence Berkeley Laboratory)*

Calculating Distance for Cepheid Variable Stars

by Adam A. Bier-high school student (http://hou.lbl.gov/studentreports/adamcv/cv.html)

	A	B	C	D	E	F
1	Image (Days)	Ref Bright	Img CV Bright	Norm Factor	Real CV Bright	
2	(Known Bright)	2.28e-12	n/a	n/a	n/a	
3	6	285847	3488	7.976295e-18	2.782131e-14	
4	8	5301	1746	4.301075e-16	7.509677e-13	
5	10	133451	80907	1.708492e-17	1.382289e-12	
6	11	111359	48670	2.047432e-17	9.964852e-13	
7	14	289890	3603	7.865052e-18	2.833778e-14	
8	15	289707	72637	7.870020e-18	5.716546e-13	
9	18	271794	152711	8.388706e-18	1.281047e-12	
10	21	285991	61895	7.972278e-18	4.934441e-13	
11						
12					Days	CV Bright
13					6	2.782131e-14
14	Average CV Bright ------->		6.915060e-13		8	7.509677e-13
15	[Calculated as SUM(F13...F20)/8]				10	1.382289e-12
16					11	9.964852e-13
17					14	2.833778e-14
18					15	5.716546e-13
19					18	1.281047e-12
20					21	4.934441e-13
21						

- Normalization was achieved by calculating Norm Factor based on ratio between known Reference Star brightness (in Joules/second/meter^2) and an image Reference Star brightness (in pixel counts).
- Period of Cepheid: 8 days (as shown in the graph below).
- Apparent brightness of Reference Star: 2.28×10^{-12} J/s/m^2 (used as B2 in the table above).
- Average apparent brightness of Cepheid: 6.1915×10^{-13} J/s/m^2 (calculated by taking the sum of the normalized brightness values and dividing it by 8, the number of values; shown as C4 in the table above). This gives E, the real or absolute Cepheid brightness.
- Luminosity of Cepheid: 1.71×10^{29} J/s (calculated by using the period-luminosity relationship to get luminosity in Solar Units, 3000, then converting that into J/s by multiplying it by 5.7×10^{25}). This gives P, the period.
- Distance to Cepheid in meters using the light/distance equation:
  $E = P / (4 \pi d^2)$
  $6.915 \times 10^{-13} = 1.71 \times 10^{29} / (4 \pi d^2)$
  $6.915 \times 10^{-13} \times (4 \pi d^2) = 1.71 \times 10^{29}$
  $8.690 \times 10^{-12} \times d^2 = 1.71 \times 10^{29}$
  $d^2 = 1.97 \times 10^{40}$
  $d = 1.40 \times 10^{20}$ meters
- Distance to Cepheid: 14,800 light-years (calculated by dividing the distance in meters by 9.46×10^{15}).



Core Activity 10.4: Variance and the Standard Deviation

Using *variance* and *standard deviation* is an even more meaningful method of measuring data variability than average deviation.

A. The determination of the variance differs from average deviation in the following manner. Instead of taking the absolute value to eliminate the negative signs, the deviations are squared. Then, instead of being divided by the number of data points, the sum of the squared values is divided by the number of data points minus one. Referring back to Table 10.5, the variance for Sample 1 is as follows:

$$\frac{(-2)^2,\ (-1)^2,\ (0)^2,\ (1)^2,\ (2)^2}{(5-1)} = \frac{4 + 1 + 0 + 1 + 4}{4} = 2.5$$

The variance for Sample 2:

$$\frac{(-1)^2,\ (0)^2,\ (0)^2,\ (0)^2,\ (1)^2}{(5-1)} = \frac{1 + 0 + 0 + 0 + 1}{4} = 0.5$$

B. The standard deviation is the positive square root of the variance. Therefore for sample 1 the standard deviation (**SD**) is:

SD $= \sqrt{2.5} = 1.6$

For sample 2:

SD $= \sqrt{0.5} = 0.71$

Comparison:

Sample 1 – average deviation = 1.2, **SD** = 1.6

Sample 2 – average deviation = 0.5, **SD** = 0.71

The standard deviation shows a larger deviation than the average deviation leads us to believe. While this may seem a strange and confusing way of measuring variability, try to understand this method in the following way. If you ignore the square root for a moment and just consider the variance, this expresses the average of the *squared* differences between the values and the average, rather than the average of the absolute differences.

Squaring the differences causes the expression to be dominated by the largest differences, while the comparatively small ones become insignificant. This has the net effect of emphasizing large deviations from the average, while de-emphasizing small ones. For example, 2 squared = 4, while 5 squared = 25, a much larger number. Squaring the larger number makes a larger impact. As a result, the expression inside the square root is considerably more "sensitive" than the average deviation.

In summary, to calculate the standard deviation:

1. Calculate the average of the data set.
2. Subtract the average from each data point to find the difference.
3. Eliminate the negative signs and square the differences.
4. Add the squared differences together.
5. Divide the sum by the number of data points minus one.
6. Take the square root of the result.

The numerical expression for this method is as follows:

$$\text{variance} = \frac{\Sigma\ (x_i - \bar{x})^2}{n - 1}.$$

and standard deviation (SD) = the square root of the variance, therefore:

$$\text{SD} = \sqrt{\frac{\Sigma\ (x_i - \bar{x})^2}{n - 1}}.$$

where $\mathbf{x_i}$ = the value of each data point
$\bar{\mathbf{x}}$ = the average of all the data points
Σ = the Greek letter sigma, meaning “sum of”
$\mathbf{n}$ = the total number of data points

1. To calculate the standard deviation for the Star X data:
   a. Using the individual deviation numbers you calculated for the first JD magnitude estimation from (3a) in Core Activity 10.3, square the number.
   b. Add together the squared numbers for the first JD estimation for the entire class, and divide by the number of data points minus one. This is the variance.
   c. Take the square root of the variance. This is the standard deviation. Enter into column [G] in Table 10.4.
   d. Repeat for all the remaining magnitude numbers.

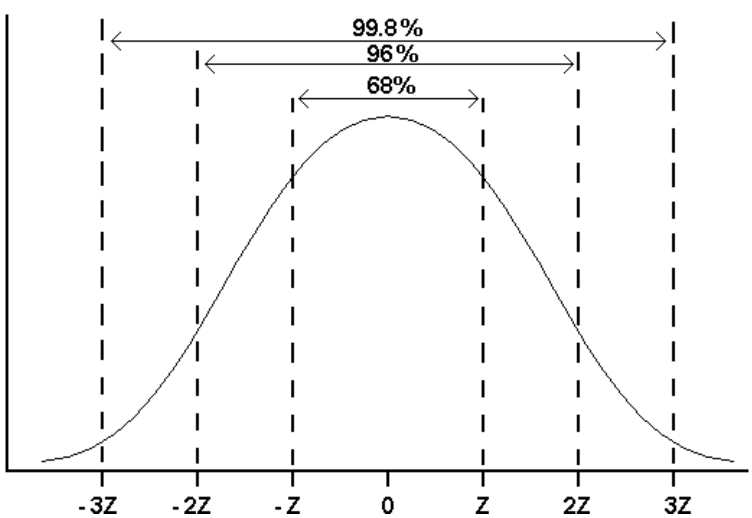
Remember, when observations are relatively precise (low variability), the standard deviation is very small. When the observations have poor precision (large scatter), then the standard deviation becomes much larger.

2. Compare your values in Table 10.4 for average and standard deviation. Compare your results with those of your classmates. Did the standard deviation change between the first and last point in Table 10.4? If so, what reasons can you suggest?

3. Find the range and the standard deviation again with only half of the class observations. How does the size of the sample affect the range and the standard deviation? Can you determine that standard deviation is a better indicator of variability than the range? How?

Standard Deviation and the Normal Curve

Standard deviation also has many other useful applications. Statisticians have created a model for random events called the *normal distribution.* This mathematically describes the likelihood of obtaining a certain value in an experiment, depending on how many standard deviations from the accepted average that value lies. If you connect the midpoint of the tops of each bar in a histogram, you will get a curve. A bell-shaped curve that closely matches the distribution of many large sets of numbers is called the *normal curve* or *bell curve*. For example, the odds of a coin-toss resulting in "heads" is 50–50, or half of 100 tosses. But if you toss a coin 100 times and keep track of the number of times you get "heads," you probably will not get "heads" exactly 50 times. But if you repeat the experiment 1000 times (100,000 coin tosses in sets of 100 each), and then draw a relative frequency histogram for the number of times you get "heads," a normal curve will result. The likelihood of a measurement being within a certain number (Z) of standard deviations from the average is assessed by finding the area under the bell curve between the points (–Z) and (Z). Statistical tables exist which give the area between (–Z) and (Z) for a range of possible Z's. The area is given in percent (%) and should be interpreted as the probability that a value will fall within Z standard deviations of the average.



In a bell-shaped histogram, we would expect about 68% of the data to lie within one standard deviation (the interval $\overline{x} \pm 1$ SD), and almost 100% within three standard deviations (the interval $\overline{x} \pm 3$ SD).

To understand what this means, consider the following set of data:

4.0, 3.9, 4.1, 4.0, 4.2, 3.9, 3.9, 4.1, 3.8, 4.0,

with an average = 4.0 and a standard deviation = 0.12.

If the measurements follow the normal distribution, then approximately:

a) 68% of the measurements fall between 4.0 $\pm$ 0.12, or between 3.88 and 4.12;

b) 96% of the measurements fall between 4.0 $\pm$ (2 x 0.12), or between 3.76 and 4.24;

c) 99.8% of the measurements fall between 4.0 $\pm$ (3 x 0.12), or between 3.64 and 4.36.

For any set of data to appear to be normal, the number of data points should be large—at least 30—and the larger the better. Then and only then an analysis of Z should be made to determine if the distribution is normal or not. The example we just considered is not a good representation of a normal distribution, even though it may give a normal curve, because the data points are fewer than 30. So let us assume that we had a large number of observations and came up with a normal curve. Now the question is, why is it so important to have a normal curve?

This concept is critical to assessing the validity of measurements, since it helps to detect errors. Almost 100% of the data will fall within three standard deviations of the average, so if we get a measurement of 4.4 in our sample data, we can assume that the measurement is probably false. However, we have to be very careful to determine whether there is any valid reason to discard this measurement. Not all unlikely measurements are incorrect. To determine the validity of the results, the *standard error of the average* is calculated.

Core Activity 10.5: The Standard Error of the Average—The Error Bar

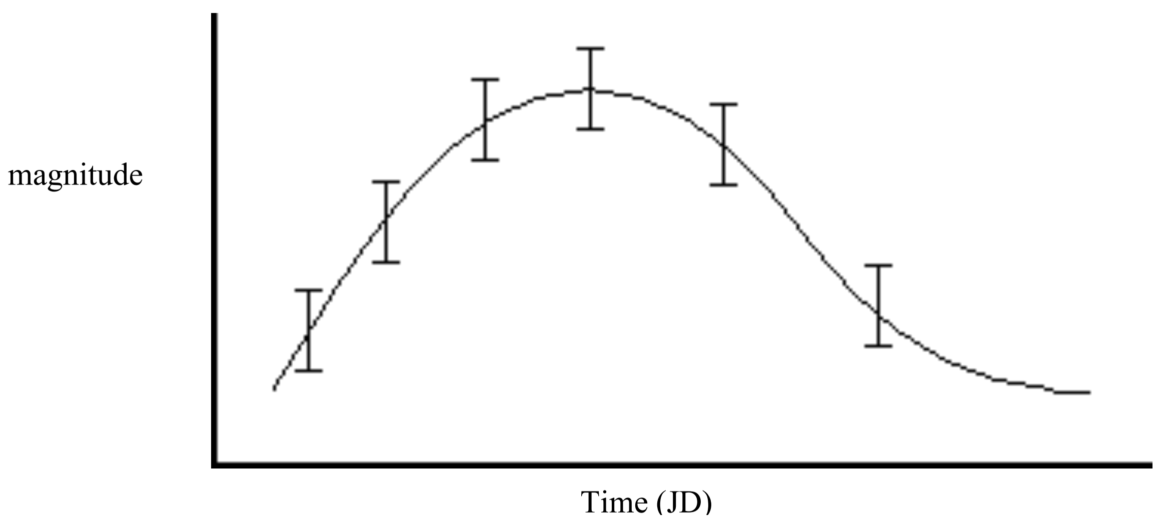
There is a mathematical calculation of the uncertainty of the average for a set of data. Since the average is calculated using a set of data that has error, the error of the average also needs to be calculated. The *standard error of the average* is the measure of how close to the exact value the average is likely to be. It is determined by dividing the standard deviation by the square root of the number of measurements. In mathematical terms:

$$\text{Standard deviation of the average} = \frac{\mathbf{SD}}{\sqrt{n}}$$

For the sample data set above (4.0, 3.9, 4.1, 4.0, 4.2, 3.9, 3.9, 4.1, 3.8, 4.0) **SD** = 0.12 and the number of observations **(n)** = 10.

Therefore $\quad 0.12/\sqrt{10} = \pm\, 0.038$

This value is used as the value of the error bars commonly seen on scientific graphs. To draw the *error bar* for this data point, you would draw a vertical line through the point on the graph with a 0.038 magnitude length above the point and a 0.038 magnitude length below the point, to produce the required .076 magnitude length for the entire bar (the error ranges from 0.038 to +0.038).



Exercise: Calculate the standard deviation of the average for the class data points for Star X and enter the result in column [H] of Table 10.4. You will use this information in the following chapter.

Mythological Evidence for Ancient Observations of Variable Stars

(*Adapted from a paper by Stephen R. Wilk, published in the journal of the AAVSO, Volume 24, 1996, pp. 129–133.)*

The known history of variable stars begins with David Fabricius' 1596 observations of omicron Ceti (Mira, "the Wonderful"). The eclipsing variable star Algol was first noted by Gemiani Montanari in 1667, but its period of 2.867 days was not measured until the 1783 work of Nathaniel Pigott, John Goodricke, and Johann Georg Palitzch.

However, there has long been suspicion that knowledge of variable stars extends much farther back in time. The variability of Algol or Mira is suggested in ancient Babylonian and Chinese texts. The names applied to Algol—Demon's Head," "Head of the Gorgon," "Lilith," "Satan," or "The Piled-up Corpses"—have a vaguely evil ring to them, which suggests ancient knowledge of peculiar properties. Another indication of ancient knowledge of Algol's variability is its rarely-cited Hindu name, Mayavati, meaning "The Changeful."

A case has been made for ancient Greek knowledge of variable stars on the basis of Greek mythology. Perseus, son of Zeus and Danae, was sent by the tyrant Polydectes to obtain the head of a Gorgon. Perseus first visited the Graeae ["Grē'-ay"], sisters of the Gorgons. The Graeae had the form of old women, and had only one eye that they shared in common. Perseus intercepted the eye as they passed it from hand to hand, and promised to return it if they gave him directions to the home of the Gorgons. They did so, but according to some accounts, Perseus threw the eye into Lake Tritonis in Africa, so he could safely escape.

Perseus, Philippe La Hire, 1705

Perseus went to the island of the Gorgons and found them asleep. Two of them, Stheno and Euryale, were immortal, but the third, Medusa, was not. Perseus struck off Medusa's head and stuck it in his bag. From the severed neck sprang the winged horse Pegasus and the warrior Chrysaor, Medusa's children by Poseidon. The noise roused the other Gorgons, but Perseus was able to escape. As he returned home, Perseus passed over Ethiopia and saw Princess Andromeda chained to a rock as a sacrifice to Cetus, the sea-monster. Perseus went to Andromeda's parents, King Cepheus and Queen Cassiopeia of Ethiopia, and offered to save Andromeda, provided she was given to him in marriage. They agreed. Perseus rescued Andromeda and slew Cetus, but Cepheus and Cassiopeia later plotted against Perseus, and he turned them to stone with the Gorgon's head.

The constellation of Perseus has been associated with the mythological character of that name since at least the fifth century BC. Later illustrations generally show Algol forming one of the Gorgon's eyes, but Roman and Arab authors call the star the head or face of the Gorgon. A more reasonable interpretation of the periodic fading of Algol is that it represents Perseus cutting off Medusa's head and placing it in his bag.

Algol B eclipses Algol A approximately every third day. This could explain why there are three Gorgon sisters, and why only Medusa is mortal. The two days during which Algol is not eclipsed represent the two immortal sisters, Stheno and Euryale. Medusa is the third day, during which the star is eclipsed, and the Gorgon "loses her head."

The eclipsing of Algol can be interpreted another way within the same myth. The three Graeae are virtual doubles of the Gorgons-they are both sets of three sisters, and they share the same parents. Maybe they, rather than the Gorgons, are the actual monsters from a parallel version of the myth, in which the task set to Perseus was to steal the eye of the Graeae. The fading of Algol in this case represents Perseus intercepting the eye (Algol) as it is passed from one sister to another.

There is an interesting corollary to this interpretation. The spectacular Perseid meteor shower every mid-August appears to originate from the arm of the constellation of Perseus. It is very easy to see in the display Perseus hurling the eye of the Graeae into Lake Tritonis.

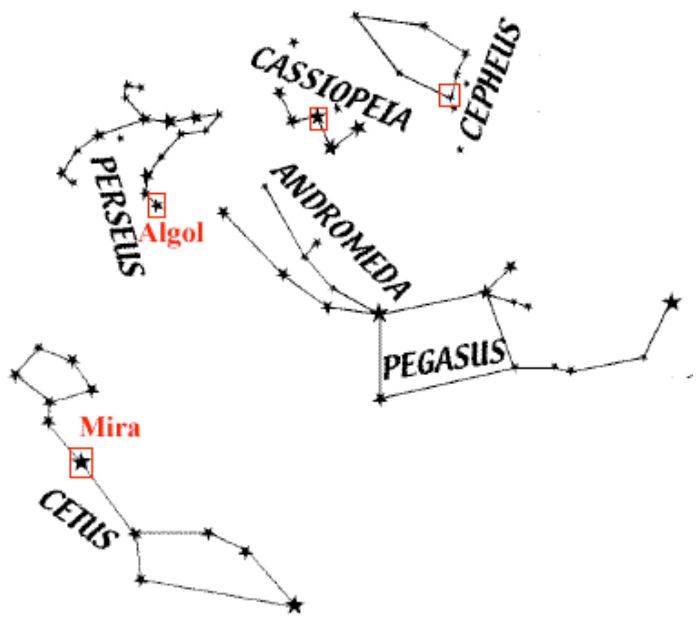


Figure 1.

It is also notable that the constellations representing characters in the myth of Perseus and Andromeda are grouped so close together in the sky (Figure 1). Most of these constellations harbor naked-eye variable stars. Three of them are so noticeable that they have given the names to their types. Algol, the preeminent example of eclipsing variables, has already been mentioned, as has Mira (omicron Ceti), the first historical variable star to be officially discovered.

Goodricke, co-discoverer of Algol, also discovered delta Cephei, the prototype for Cepheid variables. One must also note that gamma Cassiopeiae, the center star of the "W" of Cassiopeia, is an irregular variable star which varies between 1.6 and 3.1. Besides Algol in Perseus, that are naked-eye variable stars in the constellations of Cetus, Cepheus, and Cassiopeia. These are all constellations representing Perseus' enemies in the myths. In addition, Cetus is the mother of both the Gorgons and the Graeae.

Evidence of this sort can never be certain, but the set of coincidences strongly suggests that the ancient myth-makers and proto-astronomers knew of the variability of Algol, Mira, delta Cephei, and gamma Cassiopeiae, and on that basis associated their constellations together in a common myth.

There are other myths and interpretations associated with Perseus. One of the oldest and most peculiar images associated with Perseus, the birth of Chrysaor and Pegasus from the neck of Medusa, is first referred to in one of the most ancient Greek poems extant-Hesiod's *Theogeny*. The real meaning of this old myth is apparent from the constellations of Perseus (with Medusa's head) and Pegasus. If Hesiod's words mean that Pegasus and Chrysaor sprang from the stump of the neck that is attached to the head, rather than from the stump attached to the body, then the scene is pictured in that grouping of stars. The constellation of Perseus stands in for the person of Chrysaor, springing to the East. Pegasus, the winged horse, faces and springs to the West (Figure 2).

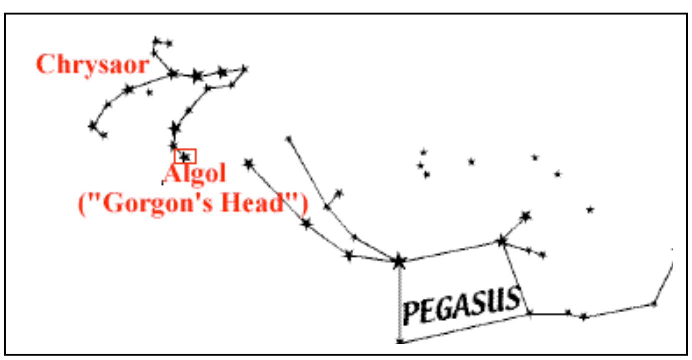


Figure 2.

The correlations between the variations of Algol and elements of the myth of Perseus and the Gorgon suggest ancient knowledge of that variability. The further association of surrounding constellations, which contain most of the naked-eye variable stars visible from Greece, with characters in the same myth, suggests that these variable stars were also known in preclassical Greece, whence the myths arose.

Activity 10.6: Statistical Analysis of Delta Cephei

If you have classroom observational data for delta Cep, use them to repeat the above processes of calculating the average and range, constructing a histogram, and calculating average deviation, variance and standard deviation, and the standard error of the average.

MATH TALK

Have you ever heard the expression, "Four out of five doctors recommend...?" Or "... 42% more relief from heartburn"? Or "...better highway mileage than any other sub-compact hatchback sedan costing under $10,000 made in America"?

Perhaps you suspected that these claims were not completely true. It is wise to be suspicious, because **statistics** (and numbers in general) can be manufactured to make any idea sound convincing. When used properly, statistics is a powerful tool for uncovering truth; when used improperly, it can be manipulated to prove almost anything.

Try, try again

There are lots of ways to misuse statistics. One way is perseverance: if at first you don't succeed (i.e., get the result you wanted), try, try again. Suppose you want to claim in a TV commercial that 4 out of 5 dentists recommend your toothpaste. You ask 5 dentists, but only 1 of them recommends your brand. So, forget you ever asked them! Ask another 5 dentists! This time, 2 of them recommend your brand. Forget them! Ask another 5! Keep trying until, by random fluctuation, you get lucky and 4 out of 5 recommend your brand. Then, show your TV commercial. Whatever you do, *do not* talk about the 13,925 dentists you had to survey before you got lucky, and don't mention that only 8% of *them* recommended your brand.

Sometimes this sort of thing happens even to honest people. If the results do not match our theory, it is too easy think of a "good" reason to believe that the data we do not like are not valid, so we have to do the experiment again. This happens far too often in scientific research, even today. Despite people's best intentions to be fair, there is just too much temptation to rationalize away the "bad" data. However, you rarely see any scientists rationalize away the "good" data, the data which support their theories!

Here we have the first lesson of honest statistics: you cannot ignore the data that do not fit your theory. Sometimes you have good reason to believe some piece of data should be excluded because it is just a mistake. But in your scientific report, you have to say so, and state exactly why it has been omitted. You can exclude data if you have good reason, but you cannot ignore them, or fail to report them.

How many?

A nursing home recently tried new procedures designed to reduce the number of accidental injuries to patients. They were pleased to announce that in the first four months of the year, patient accidents were down a whopping 60% compared to last year. Can't argue with that!

Or can you? How many are we talking about here? If last year there were 50 accidents, and this year only 20, then they are down 60%, and there is no doubt that this result is statistically significant. The chance of that happening by random fluctuation ("by accident") is less than 1 in 10,000.

But suppose there were 5 accidents last year, and only 2 this year. Yes, they are down 60%. But no, this result is *not* significant. The chances are better than 1 in 4 that this could happen by random fluctuation.

We have already seen that as we acquire more data, our results become more precise. They also become more *reliable*. Sometimes, an early result is based on so little data that it has no real significance. Do not put too much faith in statistical results (not even a whopping 60%) until you know how much data went into them.

Survey says!

Suppose two politicians are debating a school funding bill. They both try to show that the public is on their side by conducting a survey. Politician **A** wants to show that people favor the bill, so his survey asks, “Should we invest more in our children’s future by passing the school funding bill?” Lo and behold, people *do* want to invest in their children’s future, so most people say yes, and politician **A** announces that the vast majority favor his bill.

Politician **B** wants the bill to fail, so his survey asks, “Should we raise taxes to fund more and bigger government bureaucracy by passing the school funding bill?” Not surprisingly, people do not want higher taxes and more bureaucracy, so they mostly say no, and politician **B** claims that the vast majority oppose the bill.

This may seem like an exaggerated example, but it is not. This actually happens! Almost every political survey is deliberately designed to get a specific response. The questions are usually phrased to make the desired response sound good, while making the undesired response sound very bad. By doing so, the questions bias the subject’s opinion about the topic of the survey. Not surprisingly, whoever paid for the survey usually gets the response they want. Politicians are not the only ones who do this. Advertising surveys are carefully designed to make the company product look good while making the competition look bad.

Even if you are trying very hard to be fair, it is actually quite difficult to phrase the question in a way that does not influence anyone’s response. There are other ways surveys can go wrong, too; designing an accurate survey is a very difficult task, requiring much expertise. There are some organizations that do it well; for example, the Gallup organization specializes in conducting fair, scientifically reliable surveys. Still, it is an unfortunate fact that *most surveys just cannot be trusted* (especially political and advertising surveys).

What are you trying to prove?

It happens regularly that a government agency or private commission launches a major study of an important social issue. Too often they begin by announcing that they are going to prove some theory, which has important consequences for social policy. You can bet big money that they *will* find proof. After all, they have already made up their minds!

Any study which begins by assuming the correct answer, then looks for proof, will fail to give serious consideration to the possibility that the assumed “correct answer” is *not* correct. Any scientist who has already decided before the experiment that one result is “right” and another is “wrong” is no scientist at all.

It is very hard to avoid all bias when taking data. That is why we work very hard to make our experiments ***double blind***: we arrange that neither the scientists taking data, nor their subjects, know how the data will affect the outcome. For example, suppose we want to study the effectiveness of a new headache pill. We give half our subjects the new medication, while the other half get an inert sugar pill. We have to be sure that the subjects *do not know* which one they are getting. We also have to be sure that the scientists taking the data also do not know (at least until all the data are in). Otherwise, there is far too much temptation to "nudge" the data the way we want them to go.

Accidents happen

We have said that the standard of "unlikeliness" in statistics is 0.05, or 5%, or a 5% ***false-alarm probability***. This means that if we do a scientific experiment, and get a result that's only 5% likely to happen by accident, we have evidence that it is not an accident. We can write our results in a scientific paper, and every statistician will agree that our evidence is significant.

So we have evidence, but we do not yet have *proof*. After all, there *is* a 5% chance that it *did* happen by accident. Accidents do happen! In fact, an accident that is only 5% likely will happen about 5% of the time. After all, with a 5% false-alarm probability, we will get some false alarms.

Suppose a university employs 100 scientists, and each one does a different scientific experiment. From probability theory, we *expect* 5% of them to get a result that's only 5% likely, *by accident*! So *just by accident*, about 5 of the 100 scientists will get evidence that they can call "statistically significant" and publish in a scientific paper.

And they *do* have evidence, strong enough that their claim deserves further study. But they do not have proof. That is one of the reasons scientific experiments have to be *repeated*. If you get a "significant result" once, you have evidence. If two people get the same result, there is very strong evidence. If a dozen people do the same experiment, and they all get a significant result, then we can start to believe it.

Every year, scientists do hundreds of thousands of experiments. If they use a 5% false-alarm probability (and most of them do), we can *expect* 5% of the results to be false alarms. Five percent of 100,000 experiments is 5,000 false alarms! That means 5,000 results that seem to be significant, but really happened only by accident. Some of them will be published in important scientific journals. And they should be published: they are all *possibilities*, and deserve further study. But for most of them, we should not be convinced until the results are repeated.

Conclusion

We have seen that if you want to deceive people, statistics makes it easy. In fact, even if you want to be honest, there are so many things that can go wrong in an experiment or a survey, that we must carefully guard against bias. Even if we succeed, and get an unbiased result which is "statistically significant," it still might have happened just by accident. So the experiment has to be repeated, many times, and each time requires the same care in guarding against any bias which could affect the results.

That is a lot of work! Still, the payoff makes it well worth it. Not doing so gives us half-baked theories which sound good but really are not, supported by biased data and invalid statistics. This is worse than ignorance! But if we invest the effort to do science well, we reap the reward of knowledge that we can trust, and often can put to very good use.

Unit 5: ANALYSIS OF VARIABLE STARS

Variable star data have many advantages for teaching science and math skills. You will be using real data, most of them useful for astronomical research. They contain real errors, which must be understood and measured before the results can be interpreted. The next five chapters deal with the mathematical analysis techniques which must be applied to the variable star observational data. Chapter 10, "Statistical Concepts," introduces the concepts of scatter, range, average deviation, and standard deviation. Chapter 11, "Variable Stars, Light Curves, and Periodicity," discusses the different types of variable stars and the characteristics of their light curves, which are plots of magnitude versus time, and the most important graphs in variable star astronomy. Chapter 12, "Variable Stars and Phase Diagrams," introduces phase diagrams and utilizes the VSTAR software program for more in-depth analysis of period determination. Chapter 13, "Variable Stars and O–C Diagrams," is an introduction to prediction and O–C diagrams, a more advanced method of analyzing periods and the differences between observation and prediction.

CONTENTS FOR UNIT 5

Chapter 10: Statistical Concepts

This chapter introduces the statistical concepts necessary to analyze and interpret variable star data. Histograms, relative frequency, variability (range, average deviation, variance, standard deviation, the normal curve), and error bars are presented.

Chapter 11: Variable Stars, Light Curves, and Periodicity

This chapter discusses different types of variable stars and introduces light curves, the most important graphs in variable star astronomy. It discusses the characteristics of variable star light curves and demonstrates how to plot and interpret them.

Poster Page: Radar Guns and Speeding Stars
Space Talk on DI Her–A Puzzling Binary System

CHAPTER 12: VARIABLE STARS AND PHASE DIAGRAMS

This chapter introduces phase diagrams, which show the average behavior of a star during its cycle and determine the accuracy of the measured period. Mathematical and computer techniques for determining periodicity are also presented utilizing the VSTAR software program.

Investigation 12.1: Periodic Cycles
Core Activity 12.2: Folded Light Curve of the Variable Star SV Vul
Core Activity 12.3: Another Folded Light Curve of SV Vul
Core Activity 12.4: Yet Another Folded Light Curve of SV Vul
Poster Page: SS Cygni
Activity 12.5: Folded Light Curve of Star X and Delta Cep
Core Activity 12.6: VSTAR
Space Talk on Mira Stars
Poster Talk: "Theoretical Glue"

CHAPTER 13: VARIABLE STARS AND O–C DIAGRAMS

This chapter introduces the concept that processes that are periodic are predictable. For periodic variable stars, astronomers can use prediction to plan their observation of the stars, and also to look for deviations from periodicity. This chapter introduces the O–C diagram, which can determine deviations from predicted values.

Investigation 13.1: Constructing an O–C Diagram
Core Activity 13.2: Understanding O–C with Miras
Core Activity 13.3: Prediction of SS Cyg
Activity 13.4: Prediction and Observation of Delta Cep
Poster Page: Universal Models
Core Activity 13.5: Prediction and Analysis of the Period of R Cyg
Activity 13.6: O–C for Eclipsing Binary Stars
Space Talk on The Eclipsing Binary
Poster Page: The Birch Street Irregulars

Relationship to National Science Standards and Benchmarks

Benchmarks discusses *The Nature of Mathematics* and the fact that students need to perceive mathematics as part of the scientific endeavor, and must comprehend the nature of mathematical thinking. This unit focuses on two of the sections involving *The Nature of Mathematics: Patterns and Relationships* and *Mathematical Inquiry.* The students will develop mathematical models to represent variations in stellar behavior and to predict future behaviors. Mathematical analyses will show how well further observations match the expected behaviors. From these analyses, it is possible then to develop further mathematical manipulations to study the differences between the observed and calculated variations.

In the *National Science Standards* content standards dealing with *Evidence, Models, and Explanation* and *Constancy, Change, and Measurement,* mathematical models represented by equations, graphical models of several types, and computer models and analyses are supported as necessary for scientific inquiry.

In the *Science as Inquiry* content standard, the national standards promote the use of computers for collecting, analyzing, and presenting models of events. It states that students need to be able to access, gather, store, retrieve, and organize data using appropriate software. Students will need to formulate and revise explanations for stellar behaviors when the predictions from their investigations do not match further observations. Alternative models and explanations will need to be developed. In this unit, students will produce graphical and computer models which behave in the same way as the objects under investigation. They will make predictions which then can be verified by further observations, and analyze the differences between prediction and observation to develop alternative models and explanations. Students will see that mathematics, especially statistical analysis, is an integral part of the development of scientific knowledge and understanding.

Chapter 10: Statistical Concepts

Summary

This chapter is an introduction to the statistical techniques important in the study of variable stars. The following concepts are presented: range, relative frequency, histogram, average deviation, standard deviation, normal distribution, the normal curve, and error bars. The students will use the data for Star X from Core Activity 6.5 to learn how to apply these concepts to the analysis of stars that vary in magnitude.

Terminology

average deviation	histogram	sensitive
bin/bin value	normal curve	standard deviation
double blind	normal distribution	standard error of the average
error bar	range	statistics
false-alarm probability	relative frequency	variance

NOTE: If you have high school or college students with good mathematical knowledge and abilities, a more technical version of "Statistical Concepts" is available. This alternate version of Chapter 10 can be found on the HOA web page, or you can order a hard copy from the AAVSO.

SUGGESTIONS FOR POSTER PAGES, INVESTIGATIONS, AND ACTIVITIES

Investigation 10.1: Finding the Average

You may want to do only either height or arm length, depending on your class. They will be using only one data set to construct a histogram at the end of Core Activity 10.2. There are several variations to this activity if they need more practice. Is foot length related to height? To arm length? Will the students decide to remove their shoes? If not, the different heights of their shoes will affect the measurements. Where on the arm will they start the measurement? Will they all decide on the same spot? Will everybody be able to use *exactly* that same spot? Students may try to control some of these variables. Whether or not they can, there will be a range of different results. Students should see that there is less scatter when the measurements for the entire class are averaged together. Have students discuss the different random and systematic errors that are involved with their measurements.

Core Activity 10.2: Constructing a Histogram

Histograms are used extensively. They are bar graphs that show the relative frequency with which numbers or events occur. Show your students that histograms are a popular tool for visualizing mathematical results.The newspaper *USA Today* usually has several examples each day, related to such topics as manufacturing, politics, consumer goods, and sales. Use every opportunity to show students that a technique which appears in a science class or textbook has applications in the outside world.

Core Activity 10.3: Finding the Average Deviation

Students will now start using the information from Table 6.6 with the class estimates for Star X. The answers they calculate will depend upon the data in Table 6.6. If your students do not have the ability to handle the equation for average deviation, then they can simply use the written summary within the activity. Students who feel uncomfortable with math will be surprised to find that the words they have been using to perform a math function actually has a formula which would once have intimidated them.

Poster Page: Hands-On Universe

The Hands-On Universe (HOU) program provides comprehensive curriculum activities that integrate many of the topics and skills outlined in the national goals for science and math education with open-ended astronomical investigations. HOU is currently developing activities and tools for middle school students and informal education centers, as well as implementing HOU in regional high school networks around the world. Curriculum developers at TERC (Technical Education Research Center) have created a set of seven curriculum units and teacher notes for high school classes. These have been piloted and field-tested in several schools, and other activities and units are currently under development. In addition to the curriculum units, HOU professional development workshops are available. To see what is available, access the HOU website. Their address is http://www.handsonuniverse.org.

Core Activity 10.4: Variance and the Standard Deviation

Once again, the equation does not need to be used in this activity unless your students have the ability to handle it. The analysis of standard deviation (SD) differs from average deviation only by squaring the values instead of taking the absolute value. The students should recognize that the SD gives a larger deviation from the mean than the average deviation and therefore is more “sensitive”—or, rather, gives a more accurate deviation.
The answers to the exercises are not given, as they depend upon the magnitude estimates for Star X. Remember, in this curriculum the answers are not right or wrong. We are concerned only with the process. Whatever the students get for answers *are* the answers. This is real science. We are looking for the answers because we do not know what they

are, so the results have no "wrongness" or "rightness" to them. This is true of all the observable variable star data gathered. What you see is what you get. The analysis of the data will either reveal any poor measurements or blend them into the averaging techniques. What is important is that students discuss among themselves and with you what the results mean so that they can acquire an understanding of the process.

Core Activity 10.5: The Standard Error of the Average—The Error Bar

The students will be using the error bar analysis data in Chapter 11 when they actually graph the light curve for Star X.

Poster Page: Variable Star Mythology

RESOURCE

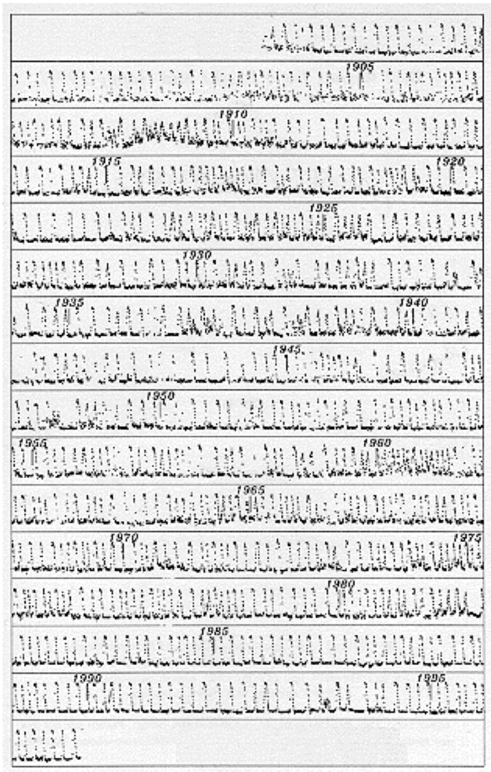
Many variable stars are observable with the unaided eye and have quite possibly played a role in developing mythologies. This poster page is an interesting research-based editorial concerning the story of Perseus, Cassiopeia, Andromeda, Cepheus, and Pegasus. An excellent movie about these constellations is *Clash of the Titans*. (See Resource List for details). NOTE: If you have younger students you may want to erase one brief scene of Perseus' mother walking nude along a beach. Otherwise, it is a family film with no obscenities, nudity, or excessive violence. It is long, however—nearly 2½ hours. There are other unaided-eye variables that may have contributed to mythology, and it is a rich topic for research.

Activity 10.6: Statistical Analysis of Delta Cephei

VSTAR

If your class (or any student) has been observing delta Cep, they can now repeat the steps they followed for Star X to produce the same analysis for delta Cep. Or you may elect to access the VSTAR database and select a series of observations for delta Cep or some other variable star. Different groups of students could be assigned different variables, and then compare their results.

Chapter 11: Variable Stars, Light Curves & Periodicity



100-year light curve of AAVSO observations of the variable star SS Cygni

Introduction

Variable stars are, quite simply, stars that change brightness. More than 30,000 are known and catalogued, and many thousands more are suspected variables. Their light variations are a vital clue to their nature, but professional astronomers do not have the time or the telescopes to monitor the brightness of thousands of variables night after night; their efforts are directed toward understanding specific aspects of the stars using such sophisticated instruments as spectrographs, photometers, radio telescopes, and satellites. Such instruments enable us to probe many different regions of the spectrum, such as X-rays, ultraviolet, infrared, and radio wavelengths. Yet it is crucial to measure the stars in ordinary visual light (the *optical* region of the spectrum) as well. The data obtained with special instruments and in shorter or longer wavelengths of light are compared with optical measurements , which serve as a benchmark. By observing variable stars, a serious observer (such as an amateur astronomer or student) can make a significant contribution to astronomy. Also, to understand and create theories about why and how stars vary, astronomers need to know the long-term history of the stars; hence it is essential that we have long-term observations. To date, the vast majority of long-term data has been provided by amateur observers.

Observations of variable stars are plotted on a graph called a *light curve* as the apparent brightness (magnitude) versus time, usually in Julian Date (JD). The light curve is the single most important graph in variable star astronomy. The light curve allows astronomers to unlock some of the secrets of stars and decode the messages hidden within the starlight. Information about the periodic behavior, the orbital period of eclipsing binaries, or the regularity (or lack) of stellar eruptions can be directly determined from the light curve. More detailed analysis of the light curve allows astronomers to calculate such information as the masses or sizes of stars. Several years' worth of observational data can reveal the changing period of a star, which is a signal of a change in the structure of the star. In the same way that a histogram is a useful tool to inspect the precision of a set of measurements, we can visualize the nature of a star's variation more easily by plotting a light curve of apparent magnitude versus time.

Light curves show that many variable stars are periodic. Periodic phenomena repeat in a regular way that is predictable. However, the line between periodic phenomena and non-periodic phenomena is not always a sharp one. Sometimes a process may seem to be periodic from a large-scale perspective, while investigation on a fine scale reveals non-periodic variations. Consider the change in apparent altitude of the Sun. If you measure the highest apparent altitude of the Sun each day for a week, you will not notice much change. The Sun seems to reach the same maximum altitude each day. Over a period of a month, however, changes will become obvious. But if we take measurements each day from December 31st until the summer solstice around June 21st, the apparent daily altitude of the Sun gets higher and higher. This is still non-periodic behavior. If we take our measurements for an entire year, from December 31st to December 31st, we will see a definite pattern. When we examine the change in the apparent altitude of the Sun over several years, we see that in addition to monthly variations, it follows a regular pattern with a period of one year.

Many variable stars do exhibit simple periodic behavior. Some semiregular variables have time intervals of periodic behavior in between non-periodic intervals. Some have two separate periodic cycles superimposed over each other, affecting the overall result. The only way to determine the periodicity is by plotting and analyzing light curves. The emerging patterns will then tell their story.

There are four main classes of variable stars: *pulsating* and *eruptive* variables whose variability is *intrinsic*—due to physical changes in the star or stellar system; and *eclipsing binary* and *rotating* stars whose variability is *extrinsic*—due to an eclipse of one star by another or the effect of stellar rotation. Below is a brief description of several different types of variable stars with their corresponding light curves. There is also more detailed information about some of the variables mentioned below throughout the *Hands-On Astrophysics* manual. A general discussion of variables is the focus of the Space Talk in Chapter 5 (pp. 87–88); the Space Talk in Chapter 7 (pp. 118–121) is about Cepheids and the distance scale; the Space Talk in Chapter 12 (pp. 225–228) is about omicron Ceti (Mira); Poster Page 12.1 in Chapter 12 features SS Cygni; and Poster Page 13.1 in Chapter 13 is about beta Persei (Algol). In addition, a summary of the different types of variable stars is included in the Appendix, and a discussion of variable stars is presented in the accompanying HOA video entitled *Variable Stars*.

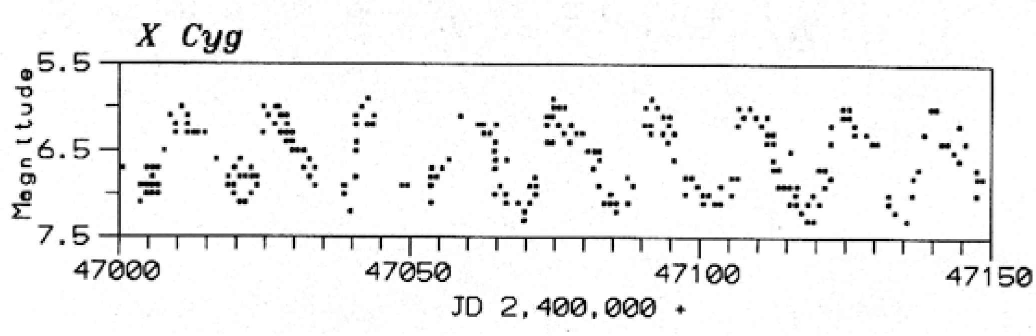
I. Intrinsic Variable Stars

A. Pulsating Variable Stars

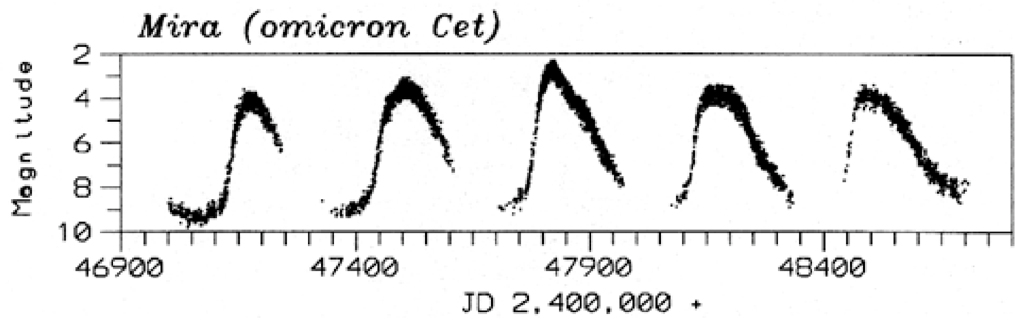
Pulsating variables change brightness because they change their size and/or shape; the whole star is actually "vibrating." Most of them simply expand and contract repeatedly, swelling and shrinking in a continuing cycle of size changes; this is known as the *fundamental mode of pulsation*. Others change not only their size, but the internal arrangement of material within the star as well. Still others change shape, alternately flattening and elongating, or showing even more complex shape changes. And to make things yet more complicated, some stars vibrate in more than one way (more than one *mode*) at the same time. Like most vibrating systems, pulsating variables repeat their changes; they tend to be *periodic*. (See the Space Talk in Chapter 12, pp. 225–228.)

One important class of pulsating variables is the *Cepheid variables*. These large yellow stars pulsate with periods from 1 to 70 days, with an amplitude of light variation up to 2 magnitudes. They are intrinsically very bright (high luminosity). The greater the absolute magnitude (luminosity) of a Cepheid, the longer its period. In fact, there is a strict relationship between a Cepheid's period and its luminosity, called the *period-luminosity relationship*. We can determine the period of a Cepheid from its light curve; then, using the period of the Cepheid, we can apply the period-luminosity relationship to compute the Cepheid's luminosity. Knowing its magnitude (how bright it appears to observers on Earth) and its luminosity (how bright it actually is) allows us to compute its distance from us, thereby enabling us to use Cepheid variables as distance markers. For example, just as astronomers in the first half of this century used Cepheid variables within the Milky Way itself to measure distances within our own galaxy, we can measure the distance to any given galaxy by computing the distance to its Cepheid variables. (See also the discussion in the Space Talk in Chapter 7, pp. 118–121.)

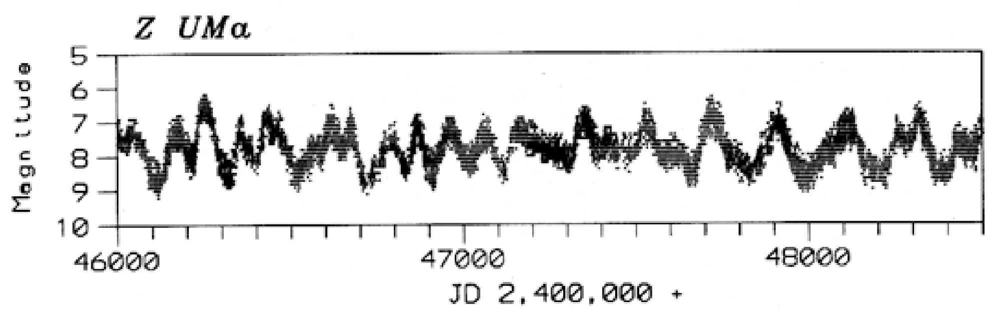
The light curve for the Cepheid variable X Cygni is shown below; each dot represents one observation. **(All observations of X Cyg, and all subsequent light curves come from the AAVSO International Database, unless otherwise noted.)**



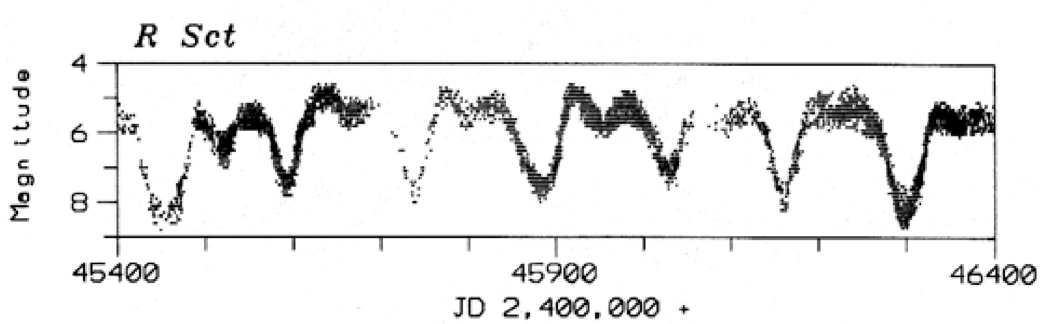
One of the largest groups of pulsating variables is the *long-period variables*, or *LPV*s. They are further divided into two major subclasses, the *Mira-type* and the *semiregular* variables. The visual light curves of Mira-type variables show well-defined periods ranging from 80 to nearly 1000 days, with amplitudes of 2.5 magnitudes or more. Mira-type variables are red giant stars, often of enormous size. Many of them are slowly ejecting a steady stream of matter into the surrounding space; this mass loss can have very dramatic consequences for their future evolution. This class of variable is named after the star *Mira* (also known as omicron Ceti), the first such star discovered (see the Space Talk in Chapter 12, pp. 225–228); its light curve is shown below.



Yet another group of pulsating stars is the *semiregular variables*. These giants and supergiants show appreciable periodicity accompanied by intervals of irregular light variation. The periods range from 30 to 1000 days, with light amplitudes of not more than one to two magnitudes. An example is Z Ursae Majoris.



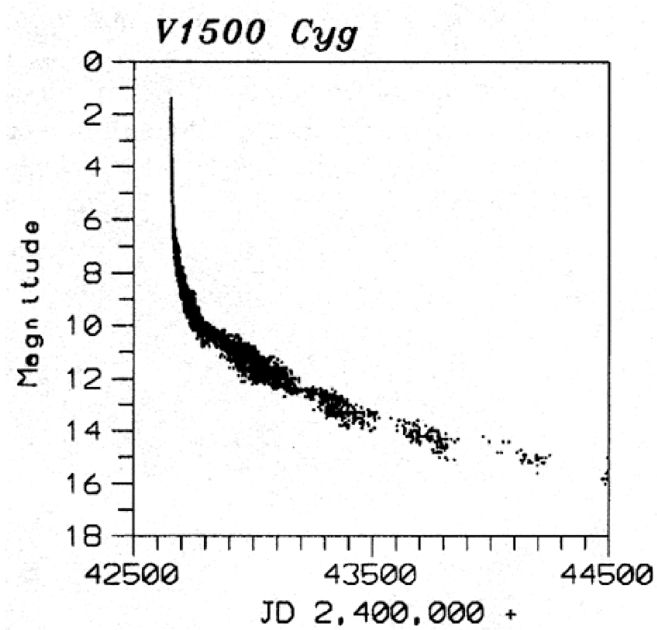
RV Tauri stars are also variables that pulsate. These yellow supergiants have a characteristic light variation with alternating deep and shallow minima. Their periods, defined as the interval between two deep minima, range from 30 to 150 days. The light amplitude may vary as much as four magnitudes. Many of these variables show long-term cyclic variations in brightness from hundreds to thousands of days. An example of an RV Tauri variable star light curve is that of R Scuti.



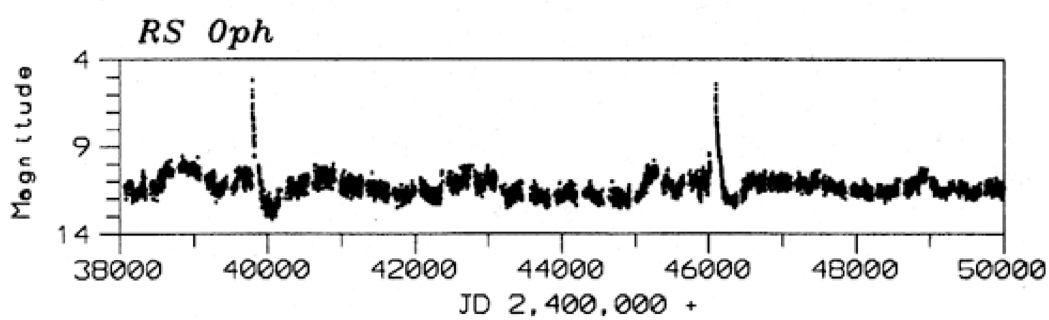
B. Eruptive (Cataclysmic) Variable Stars

Another major category of variables is the eruptive variables. These are not one-star systems, but two stars orbiting very close to each other, one of them a normal Sun-like or giant star, the other a white dwarf star. White dwarf stars are very compressed: they may pack the mass of our entire Sun into a size no bigger than the Earth. Some of the outermost material from the larger star is pulled away by the white dwarf's gravity, but this material does not fall directly onto the white dwarf. Instead, it builds up in a disk called an *accretion disk*, which orbits the white dwarf. The combination of normal or giant star, white dwarf, and accretion disk can lead to some very spectacular celestial fireworks. That is why, instead of varying smoothly like most pulsating variables, eruptive variables exhibit *outbursts* of activity, usually brightening by a large amount. The changes in their light curves are usually very unpredictable, and tend to be sudden and dramatic; that is why these stars are also called "cataclysmic variables."

Novae explosions (eruptions) occur in close binary systems consisting of a white dwarf orbiting a larger and cooler star. A layer of hydrogen-rich material is slowly accreted from the cooler star onto the compact white dwarf. The accreted material provides the fuel for the nova explosion—a thermonuclear fusion reaction similar to the detonation of a hydrogen bomb. The system increases in brightness by 7 to 16 magnitudes in a matter of one to several hundred days. After the eruption, the light slowly fades back to its original brightness over several years or decades, as shown in the light curve of V1500 Cygni at right.

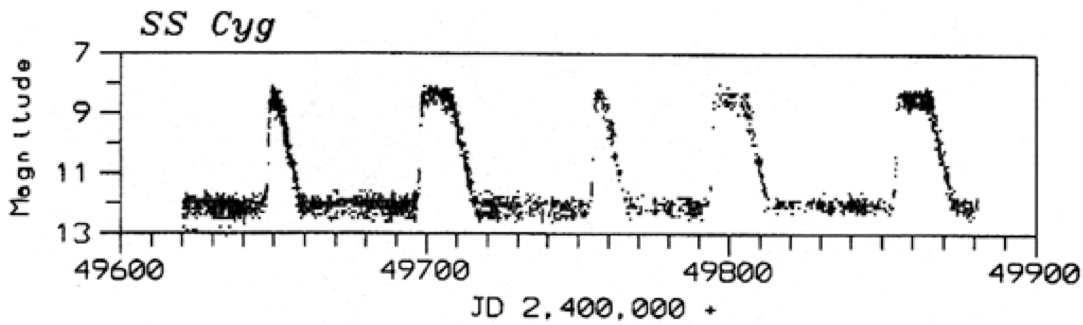


Systems which have undergone two or more nova-like eruptions during their recorded history are referred to as *recurrent novae*. Such recurrent eruptions have a slightly smaller amplitude than that which is observed in novae. An example of a recurrent nova is RS Ophiuchi.

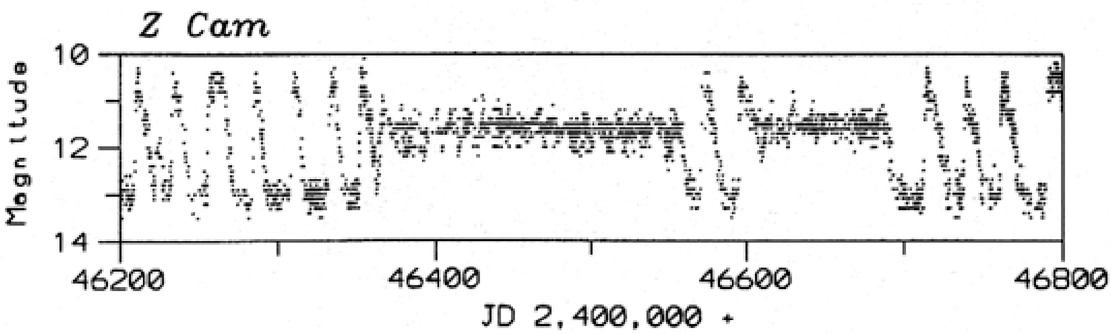


Yet another class of cataclysmic variable stars is called *dwarf novae*. These are close binary systems made up of a Sun-like star, a white dwarf, and an accretion disk surrounding the white dwarf. As matter accumulates in the accretion disk, the disk becomes unstable. Eventually, matter from the unstable disk will fall onto the white dwarf, leading to an outburst. There are three sub-classes of dwarf novae.

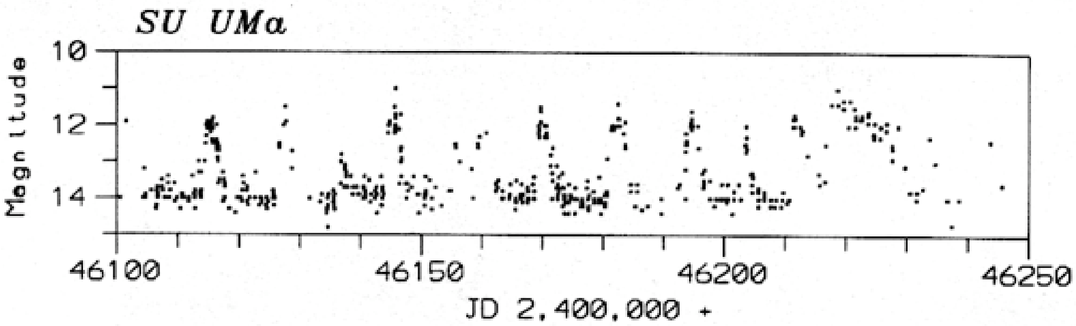
Dwarf novae of the *U Geminorum* sub-class (also called SS Cygni sub-class) are also in close binary systems, with orbital periods on the order of a few hours. After intervals of well-defined quiescence at minimum magnitude, they brighten suddenly within 1–2 days. Depending on the star, the eruptions occur at intervals of 30 to 500 days. The light amplitude of the outbursts ranges from two to six magnitudes with a duration of 5 to 20 days. An example is SS Cygni.



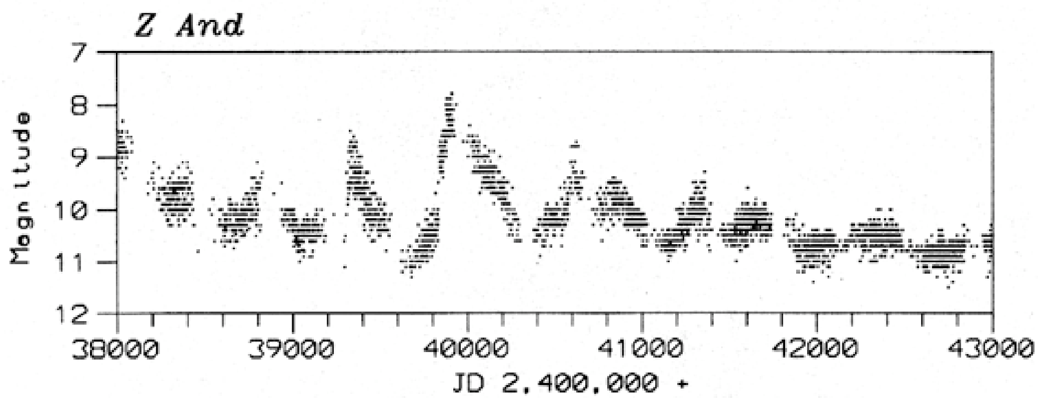
Z Camelopardalis stars, the second dwarf novae sub-class, are physically similar to U Geminorum stars. Their eruptions occur at intervals of 10 to 30 days or more; however, the quiescent level of Z Camelopardalis stars is not well-defined. In addition, the cyclic variations are interrupted by intervals of constant brightness called *standstills* (also called *stillstands*). The standstills last the equivalent of several cycles (sometimes years), with the star "stuck" at a brightness approximately a third of the way from maximum to minimum. In general, at the end of a standstill, the star continues to fade to its quiescent level, as in the light curve of the prototype star Z Camelopardalis, below.



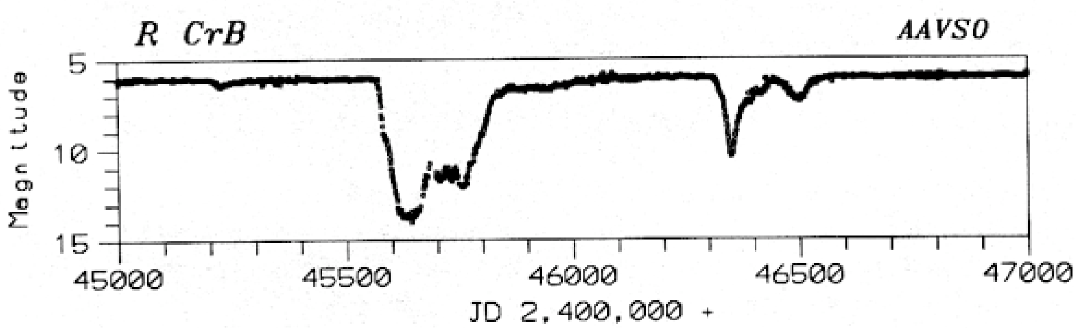
SU Ursae Majoris stars, the third dwarf novae sub-class, are also physically similar to U Geminorum stars. They have short orbital periods of less than two hours. In addition, they have two distinct kinds of outbursts: one is short, with a duration of one to several days, faint and more frequent; the other (*superoutburst*) is long, with a duration of 10 to 20 days, bright and less frequent. During superoutbursts, small-amplitude, periodic modulations (*superhumps*) appear with periods two to three percent longer than the orbital period of the system. The light curve of SU Ursae Majoris appears below; can you find the superoutburst?



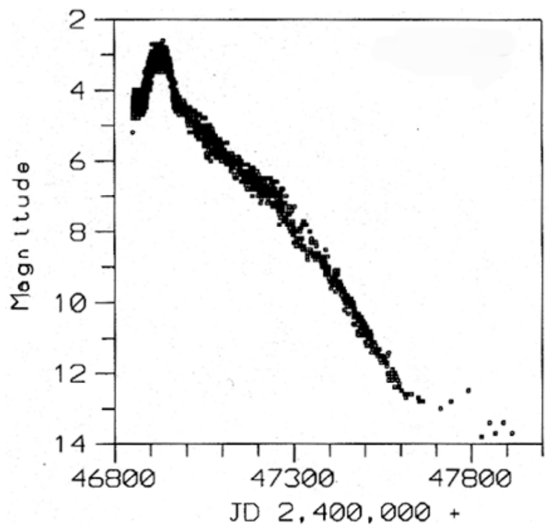
Another group of eruptive variables is the *symbiotic stars,* which display semiperiodic nova-like outbursts of up to four magnitudes. These are close binary systems with one component a red giant and the other a hot blue star. They are embedded in *nebulosity*, a region of gas and dust. An example is Z Andromedae.



R Coronae Borealis variables are high-luminosity stars (supergiants) which go into "outburst" not by brightening, but by fading! They spend most of their time at maximum magnitude, and at irregular intervals fade by one to nine magnitudes, slowly recovering to their maximum magnitude after a few months or years. The drop in brightness is believed to be caused by the formation of soot in the star's atmosphere, which is abnormally rich in carbon. When the carbon veil is blown away, the star returns to maximum magnitude. The light curve (one-day means) of R Coronae Borealis is shown below.



Perhaps the most spectacular of all variables is the *supernova*. A supernova is the violent end of a massive star during which the star quite literally explodes, blasting most of its material out into space in seconds. As a result, it can brighten by 20 magnitudes or more; a large supernova may briefly outshine the entire rest of the galaxy. The tremendous explosion will leave behind a fragment of very dense material at its center. This may take the form of a neutron star, whose material is compressed to the density of an atomic nucleus. Or it may be so compressed that it forms a black hole, a region where the gravity is so strong that nothing, not even light, can escape.



The light curve of the spectacular Supernova 1987A, which appeared in 1987 in the Large Magellanic Cloud (a dwarf galaxy near our own Milky Way), is shown above.

The material blown off in a supernova explosion is rich in complex elements such as carbon, nitrogen, oxygen, and iron. Eons later, this material can condense as part of a newly-forming star system. The enrichment of our galaxy by supernova explosions has provided the necessary complex elements to form Earth-like planets, and even life. It is no exaggeration to say that we are stardust: many atoms in our bodies, including carbon, calcium, iron, and magnesium, were synthesized within the core of a star, and probably ejected by a supernova explosion.

A supernova happens, on average, about every 300 years in a galaxy. The last supernova in our own galaxy was in the year 1054, over 900 years ago. Are we overdue?

Stars vary when they are in the stages of birth, old age, or death, all of which are periods of extreme instability in the life of a star. Many pulsating variables, for example, are near the end of their lives, and running out of their main fuel, hydrogen. Thermonuclear fusion does not simply turn on at birth and quietly turn off when the hydrogen is exhausted: fuels other than hydrogen can be burned, causing a wide variety of nuclear reactions and changes to the star's structure. The changes in the fuel economy of a star can upset the delicate balance between gravity and radiation pressure which has kept the star stable for most of its lifetime. Through the variations in their brightness, these stars "talk" to us—they try to tell us their story. Thus by studying variable stars, astronomers try to put together the puzzle of how stars evolve and die.

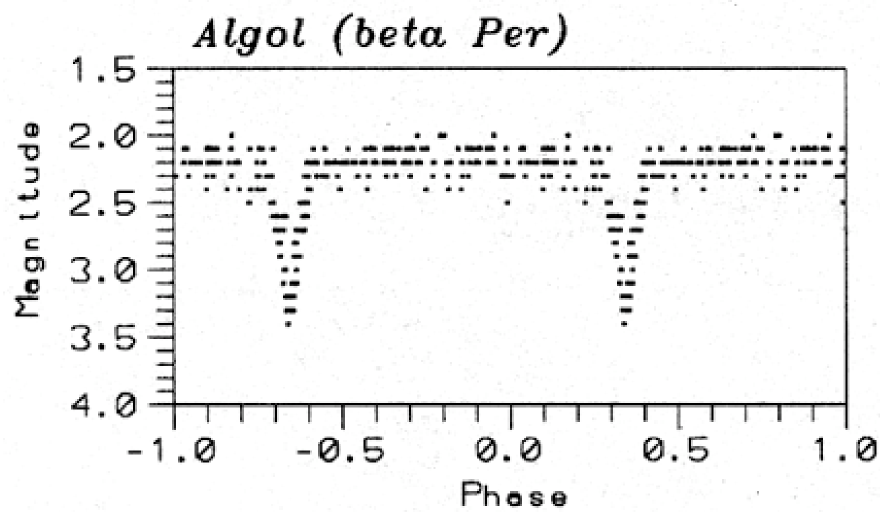
II. Extrinsic Variable Stars

A. Eclipsing Binaries

Eclipsing binaries are binary star systems whose members eclipse each other, blocking one another's light, thereby causing the system to look fainter to observers on Earth.

The light curve of an eclipsing binary depends on the sizes and brightnesses of the stars, their separation from each other, and the geometry of our view from Earth. For example, the first star may be larger, and totally eclipse the second, while the second only partially eclipses the first. The time between primary eclipses is the orbital period of the binary system. Detailed analysis of the light curve shape yields much information about the size, mass, and shape of the stars, and the shape of their orbits.

Beta Persei (Algol), whose folded light curve is shown below, is an eclipsing binary that can be seen with the unaided eye. (Folded light curves, or phase diagrams, have two or more cycles superimposed on each other. They will be examined in greater detail in Chapter 12.)

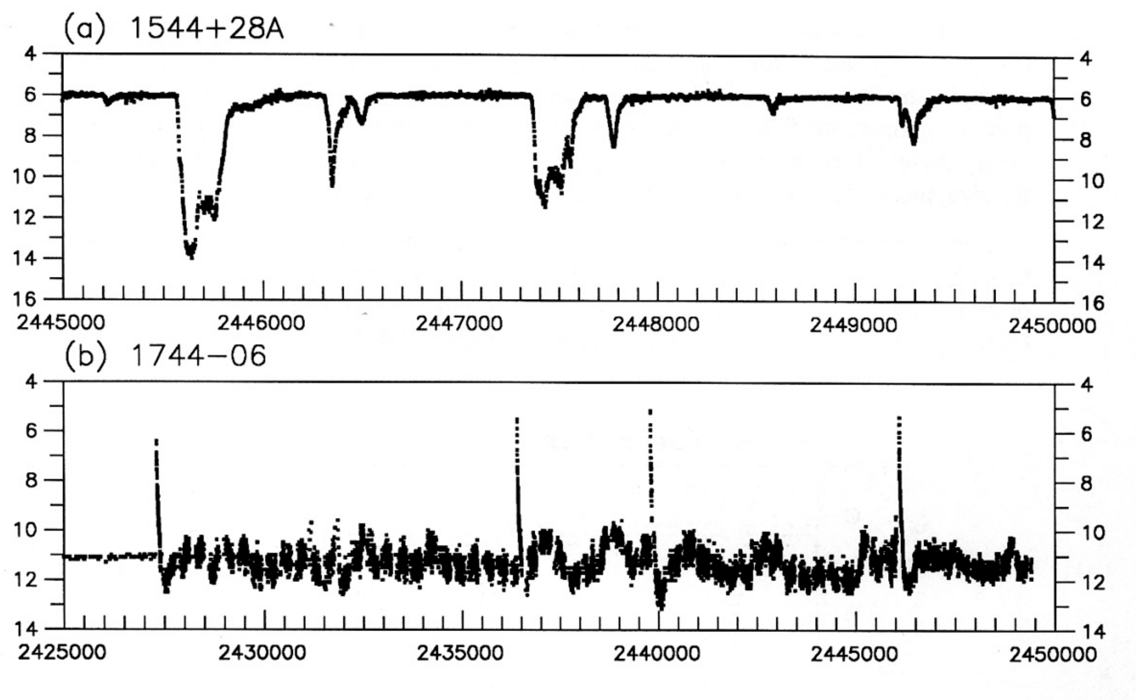


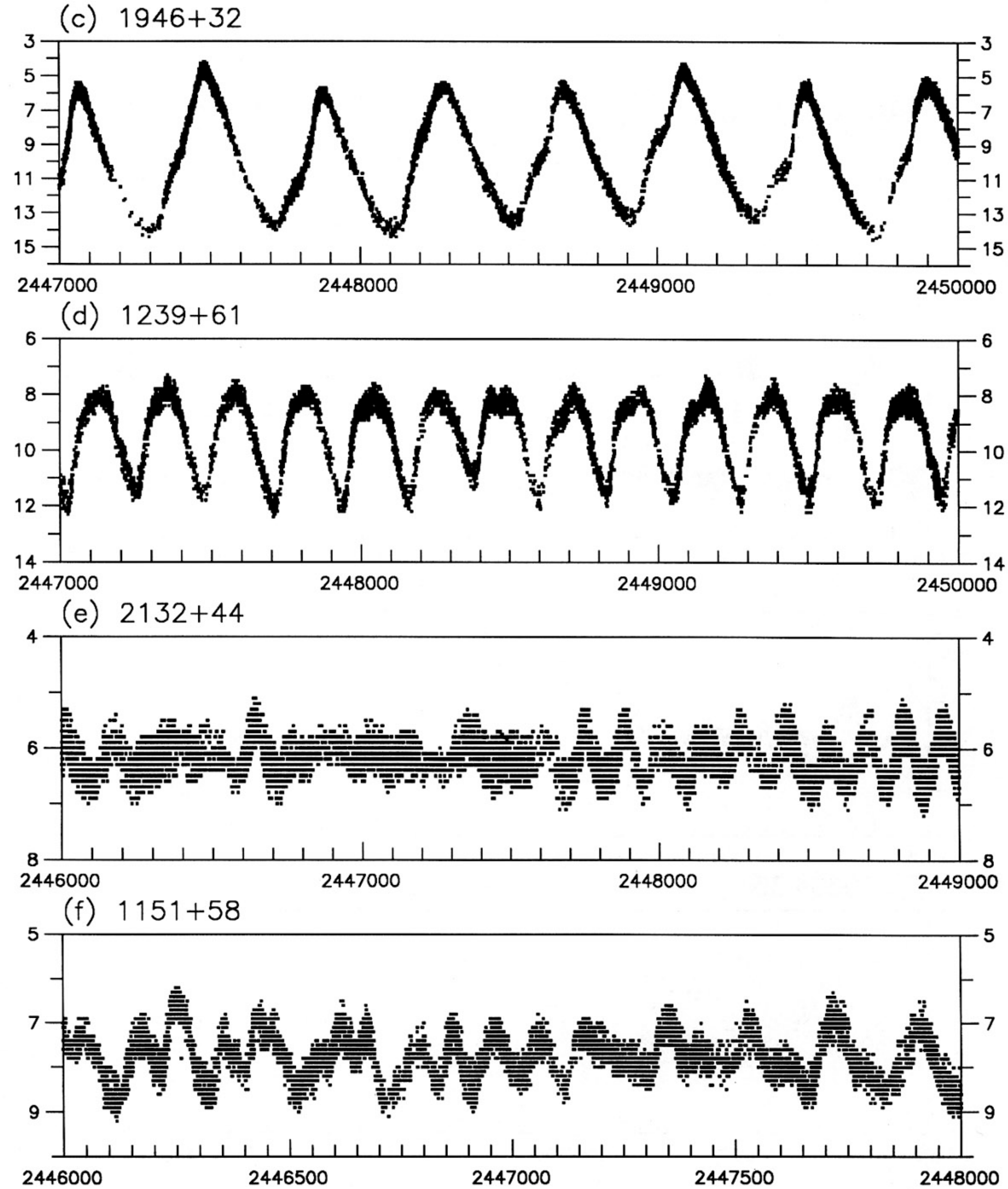
B. Rotating Variables

Rotating variables are rapidly rotating stars, often in binary systems, that undergo small-amplitude changes in light which may be due to dark or bright spots on the star's surface, similar to sunspots on our own Sun.

Investigation 11.1: Recognizing Periodic Curves

A periodic curve is one which repeats identically within a fixed time interval. Study the following curves and determine which ones seem to exhibit periodic behavior. Determine the maxima, the minima, and the periods. From the description of the types of variable stars included with this investigation, what type(s) of variable star(s) do you think each light curve represents?

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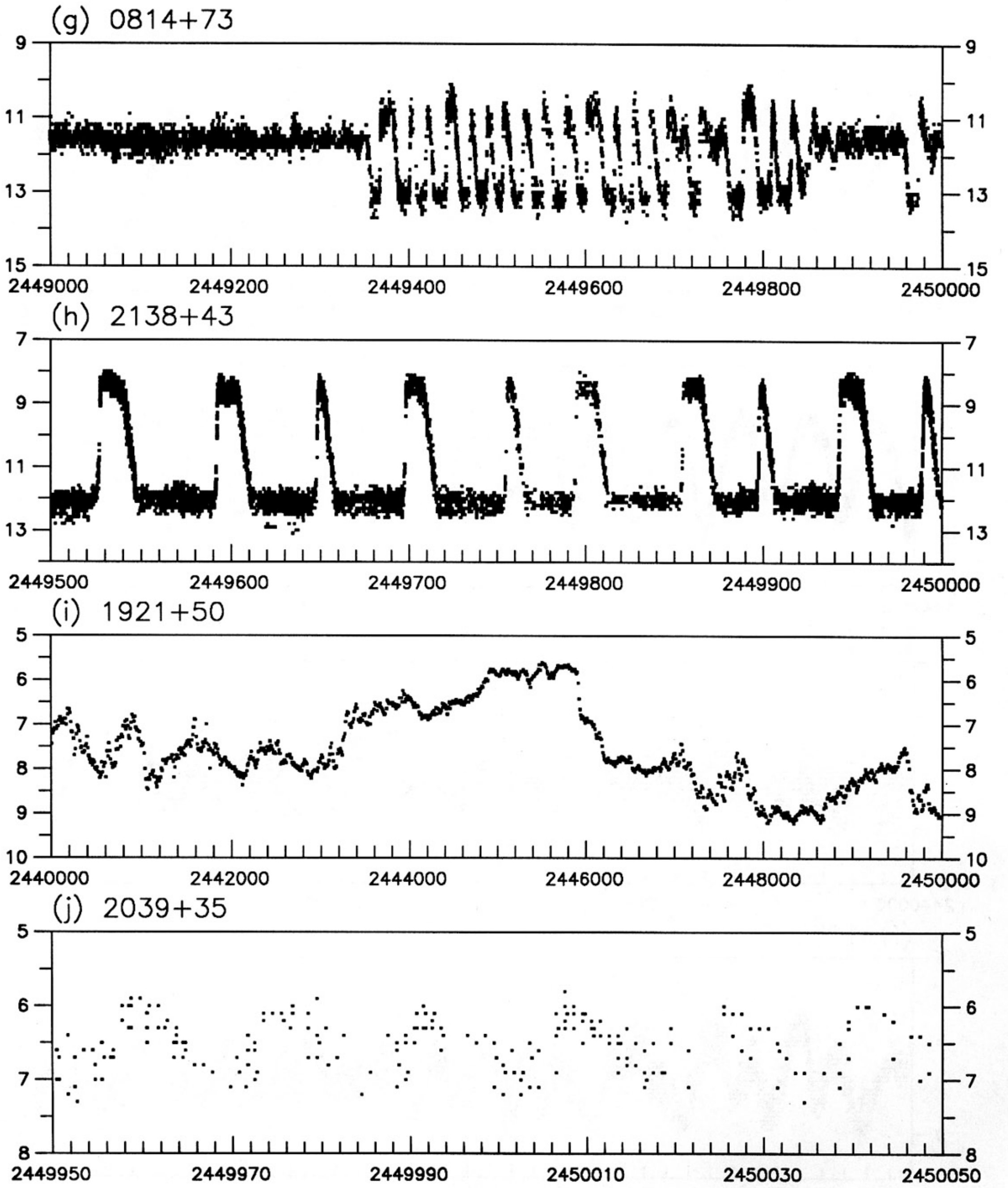
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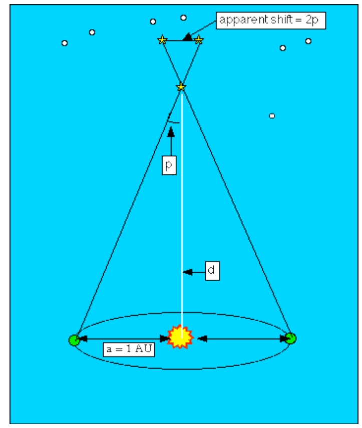
Mapping the Universe (HIPPARCOS)

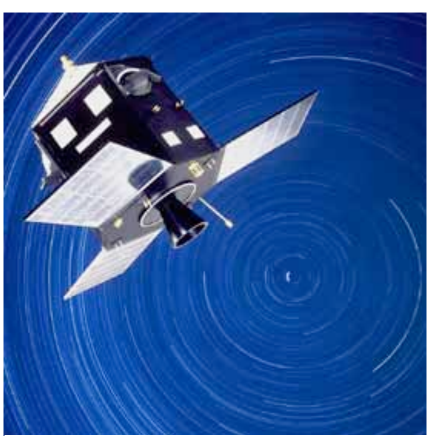


Measuring the distance to a star using parallax (p)

Astrometry is the science of measuring the positions of stars and other celestial objects utilizing a method called parallax. Parallax is the angular displacement in the apparent position of a celestial body relative to background stars when observed from two widely separated viewpoints. It is the angle that the baseline connecting the two viewpoints would subtend at the celestial object. From Earth, measurements are taken when the Earth is six months apart in its orbit around the Sun (see diagram) and the baseline is 2 AU. The angle is very small in value because the distance to other stars is so large, and is usually expressed in arcseconds (1 arcsecond = 1/ 3600th of one degree). The apparent shift for even the closest stars against the background stars is so minute that the maximum distance that can be measured directly by this method is very small. However, parallax measurements are the foundation of our knowledge of the cosmic distance scale and the age of the universe.

The HIgh Precision PARallax COllecting Satellite (HIPPARCOS), launched on August 8, 1989, measured stellar positions, proper motions (the apparent angular motion per year of a star in right ascension and declination, due to its own actual movement through space and its motion relative to the Solar System), and parallaxes. From November 1989 to March 1993, HIPPARCOS systematically scanned the sky with instruments that used the same principles as ground-based parallax measurements to measure the apparent shifting of relatively nearby stars. The resulting more accurate data have been published by the European Space Agency in a 17-volume astrometric and photometric star catalogue, *The HIPPARCOS* and *TYCHO Catalogues*. The HIPPARCOS results will have a significant impact on the scientific community and set the standard for stellar distances and motions for decades to come.

More than 200 scientists selected 118,000 stars that were the targets for the mission. These included red and white dwarfs, giant stars, radio and X-ray stars, and variable stars, including binaries. Nearly 12,000 entries in the HIPPARCOS catalogue were of variable stars. Of those, 8,200 were not previously known to be variable. Among the 2,700 periodic variables listed, there were 273 Cepheids (2 new), 187 RR Lyrae stars (9 new), and 917 eclipsing binaries (343 new). HIPPARCOS measured these to a limiting magnitude of 12.5, an astrometric resolution of 0.001 arcsecond, and a photometric precision of 0.002 magnitude. These are the HIPPARCOS catalogue data. The mission also had a second objective, called TYCHO, to survey more than one million stars down to magnitude 11.5 with an astrometric resolution of 0.025 arcsecond and photometric precision of 0.06 magnitude. These are the TYCHO catalogue data.



HIPPARCOS – Courtesy of European Space Agency

HIPPARCOS scanned the entire sky continuously, systematically, and repeatedly with a telescope capable of accurately measuring the apparent shifts in angles between pairs of widely separated stars. The angles were measured by superimposing two fields of view approximately 58 degrees apart in the focal plane of a single telescope, each field containing one of the stars in a pair. This allowed the relative separations in one direction to be measured with very high accuracy. Other directions were then measured as the spacecraft rotated with respect to the sky. Repeated accurate recordings of star-pair separations made it possible to construct an accurate star position grid in much the same way that surveyors use triangulation techniques to pinpoint features on the Earth's surface. It had been planned that at the apogee of the initial orbit the apogee-boost motor would be fired, converting the elliptical transfer orbit into a circular geostationary orbit 36,000 km above the Equator, where the satellite would be maneuvered to a longitude of 12 degrees West, a location suitable for 24-hour per day contact with the ground control station at the European Space Operations Center (ESOC) in Germany. After the apogee-boost motor fired, the solar panels and communications antennae would be deployed and the satellite would start its slow scanning motion. However, the apogee-boost motor failed to fire, which left HIPPARCOS in a low elliptical orbit that took it through the Van Allen belts, exposing the solar panels to possibly serious radiation damage. Fortunately the panels were more resistant to radiation than was thought, and the satellite still managed to collect data 60 percent of the time in spite of the highly eccentric orbit, thereby allowing Hipparcos to exceed all expectations and produce the most accurate astrometric star catalogue to date.

Hipparchus of Nicaea, a Greek astronomer who lived from 190 to 120 BC, first calculated the distance of the Moon from the Earth by measuring the Moon's parallax. Hipparchus also made the first star map and catalogue of 1,080 stars, which, when compared with observations made by his predecessors, led to the discovery of precession the shifting of the Earth's rotational axis. This was achieved by measurements with the unaided eye, the resolution power of which is limited to a few minutes of arc. These early observations were rarely accurate to more than –30 minutes of arc.

Little advance was made in astrometry until Tycho Brahe, using his brass quadrant and other recently invented instruments, carried out a long series of observations during the second half of the 16th century. His observations led to Kepler's Laws of planetary motion. In 1609, Galileo began using a new instrument for observations, the optical telescope, which led to a significant change for astrometry. The angular error in astrometric measurements fell to –15 seconds of arc in the 1600's, and to –8 seconds of arc by 1725.

Edmund Halley re-measured the rate of precession and compared the results with those of Hipparchus and others. While most stars displayed a general drift amounting to a precession of about 50 seconds of arc per year, Halley announced in 1718 that three stars, Aldebaran, Sirius, and Arcturus, were displaced from their expected positions by large fractions of a degree. Halley deduced that each star had its own "proper motion." Improvements in observational precision revealed the proper motions of many more stars, and in 1783 William Herschel found that he could partly explain these motions by assuming that the Sun itself was moving. This suggested that some stars might be relatively close to the Sun, and so astronomers intensified their efforts to detect "trigonometric parallax," the apparent oscillation in a star's position arising from the Earth's annual motion around the Sun.

Friedrich Bessel was the first to publish a parallax value for a star in 1838, following his studies of the motion of 61 Cygni. Bessel's careful analysis of the measurement errors and his use of both coordinates on the sky gave credibility to his results, after many previous claims from astronomers to have measured a stellar parallax. Thomas Henderson is credited with the first measurement of stellar parallax, that of the bright star Alpha Centauri, from observations made at the Cape of Good Hope, in 1832–33. Although he did not analyze the measurements for several years, the two components of this star, together with a faint companion called Proxima Centauri, form the nearest known group of stars to the Sun, at a distance of 4.2 light-years.

Observations improved substantially with the invention of photography. In 1887, a worldwide cooperative program among observatories from 18 countries, called "Carte du Ciel," used the same techniques and observing strategies to measure 13 million stars with a precision of –1 arcsecond. Since then, determinations of photographic trigonometric parallaxes have been made at more than a dozen observatories. The technique is to measure the shift of the selected star relative to a few stars surrounding it on some 20 or more plates taken over a number of years. Several thousand parallaxes have now been measured from the ground, but only a few hundred parallaxes are considered to be known with an accuracy of better than -20 percent of astrometric ground measurements. Any further progress on the ground was considered unlikely, since the most significant uncertainties remaining are caused by the Earth's atmosphere. In the early 1960's, some astronomers considered that the best prospect for major advances in measuring the positions and motions of stars was to go into space. The result was the launch of HIPPARCOS in 1989, with its precision in measurement in the range of milliarcseconds.

Core Activity 11.2: Analyzing the Light Curve for Star X

You have already statistically analyzed the observational data for Star X. Now you will analyze the variation in magnitude for this star by plotting the data from Table 10.4, and drawing the light curve. You may have already drawn a rough light curve and estimated the period of a star, especially if you have observed delta Cep. We will now take a more systematic approach to the analysis of variable stars.

A. Plotting Individual Observational Data

1. A light curve is a plot of apparent magnitude versus time (JD). The magnitude is always plotted on the vertical (y) axis, with the brightest magnitude number (smallest number) at the top, and the dimmest magnitude number (largest number) at the bottom. Time, in the Julian Day unit, is always plotted along the horizontal (x) axis. Construct your graph with a scale that is proportional to your data, number and label the axes, and plot your observational data for Star X. (Use your own observational data, not the class average data.)

2. Draw a smooth "best-fit" curve through your data points. Remember not to connect the dots! The individual points are not important—the general trend of the points will give us the information we want about the star's behavior.

3. Identify the regions on your graph where Star X is brightest and dimmest. The point at which a star is brightest is called its *maximum* (plural: maxima); its dimmest point is call the *minimum* (plural: minima).

   a. What are the magnitude and the time of each maximum?

   b. What are the magnitude and the time of each minimum?

4. A complete variation in light output of a variable star, from maximum to maximum or from minimum to minimum, is called a *cycle*. Has your star gone through one or more cycles? The length of the cycle (the difference between two successive minima or two successive maxima) is called the *period*. Using your light curve, find the period in days using two successive maxima or minima.

   What is the period of Star X?

B. Plotting Class Average Data

1. On the same graph, plot the class average values for Star X from Table 10.4 with a different symbol. Draw a smooth line through these points.

    a. Do the class average values give the same value for magnitude and time of maximum and minimum? Why or why not?

    b. Determine the period using two successive maxima or minima. Which result do you have more confidence in—your data or the class average data? Why?

2. In column [H] of Table 10.4, you recorded the standard error of the average for each data point. Using this information, draw error bars on all the points of the class average data in your graph. Remember, if the average for a given time is 3.5 and the standard deviation of the average is 0.032, then the true value should be 3.5 $\pm$ 0.032 magnitudes. (Since 0.032 goes to too many decimal places for your graph, simply drop the last digit.)

    Are the error bars different sizes for each point?

3. To get an idea of the nature of the variability of the star, draw two smooth curves through the error bars, one through the tops of the bars, the other one through the bottoms of the bars. The class average values, then, will be between these two curves. The area inside these two curves is referred to as the *envelope*. The band, or envelope, represents 68% of the observations within the interval of average values you selected. The larger the envelope, the larger the spread in your data measurement, and therefore the less confidence there is in the average of the interval. Likewise, the smaller the envelope, the smaller the spread and the closer the data measurements are to each other. Therefore we can have more confidence in the average of the interval.

    a. Compare your curve with the class average curve. Are there any significant differences?

    b. Does your curve fall within the envelope?

Activity 11.3: Analyzing the Light Curve for Delta Cephei

If you have classroom observational data for delta Cep and you have performed the necessary statistical analysis, plot the light curve and determine the periodicity for your data and the class average data. Construct the error bars and the envelope. Compare and discuss the results. Note: If you want to compare the results for Star X and delta Cep, or any other variable, remember that intercomparisons cannot be made unless the data are plotted on graphs with the same scale. This will make it easy for you to visually compare the differences and/or similarities of all stars you plot.

Core Activity 11.4: Pogson's Method of Bisected Chords

So far you have determined the maxima and minima by visual inspection, which may have struck you as a not-so-very-scientific approach, especially since the difference between two successive maxima or minima is used to calculate the period, and this might not be adequate information for period determination. There is a more accurate method of making this determination, called *Pogson's method of bisected chords*. This method uses neither the high points (peaks) to determine maxima, nor the low points (dips) to determine minima. Instead, the total event, the variation of the star from beginning to end, is taken into consideration. An illustration of this method is shown in Figure 11.1 below for determination of the maximum magnitude.

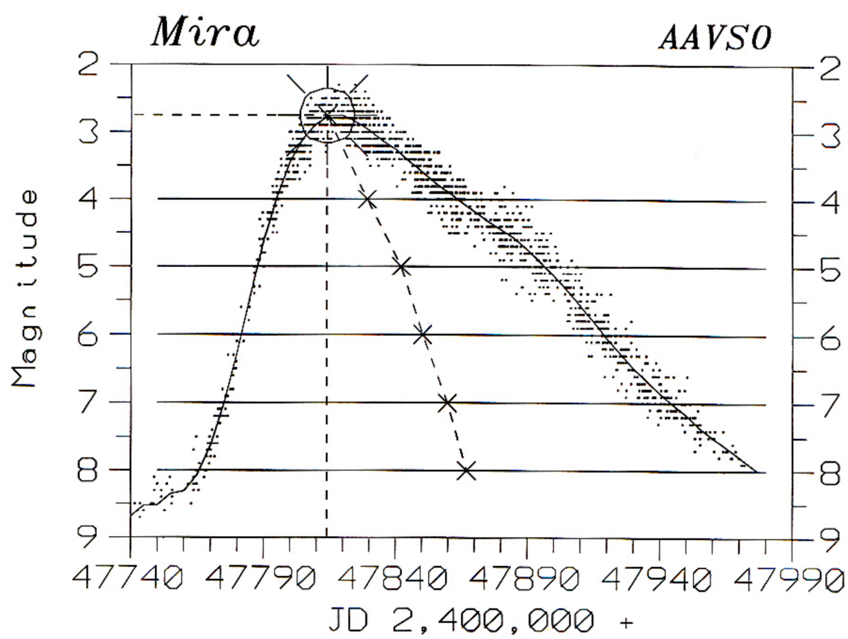


Figure 11.1

To determine periodicity with Pogson's method:

1. Using the plotted graph with the best-fit smooth light curve of V Cas below (Figure 11.2), draw several straight lines (chords). The chords are drawn parallel to the x-axis and at various magnitudes through the rises and declines of the light curve. The midpoint of each chord is measured and marked (bisected). (Refer to Figure 11.1 on the preceding page.)

2. Draw a smooth line through the midpoints of the chords and continue it upwards until it reaches the light curve. Draw a perpendicular line from this point down to the x-axis. This is the date of maximum. Read across to the y-axis from the point at which the line intersected the light curve to find the magnitude at maximum.

3. To determine the date of maximum, the chords were drawn inside the peaks. Use the same method to determine the date of minimum, only now draw the chords inside the dips. Draw a smooth line through the midpoints of the chords, and continue it downwards until it reaches the light curve. Draw a perpendicular line from this point down to the x-axis to find the date of minimum. Read across to the y-axis from the point at which the line intersected the light curve to find the magnitude at minimum.

4. The line which bisects the midpoints may be a curve itself, and there may be observations which give a brighter or fainter magnitude, respectively, than the magnitude of maximum or minimum indicated by the intersection of the midpoint line with the light curve. That is, the magnitude at maximum may not be the brightest magnitude in the cycle, and magnitude at minimum may not be the faintest. After you have determined the maxima and minima dates, calculate the period.

NOTE: Since using Pogson 's method to determine periodicity requires a large set of data, you will not be able to use Star X data for this activity, and probably not for class observational data of delta Cephei.

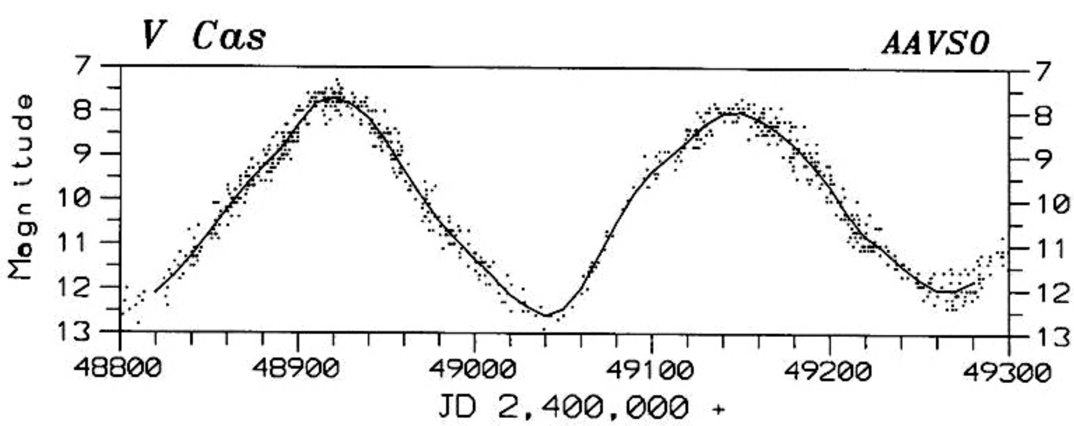


Figure 11.2

Core Activity 11.5: VSTAR

VSTAR is a flexible software package developed at the AAVSO which enables you to plot light curves and analyze them in both simple and sophisticated ways. Your instructor will give you a copy of the user's manual. Read the instructions about how to start the program, how to load data, and how to change the view. Learn how to choose which time range of data to load, and learn how to change the limits of JD and magnitude in the on-screen plot.

VSTAR includes an archive of data from AAVSO observers for several stars. Let us use this program to study some of the data in its archive. Run the VSTAR program, and load data from the "ARCHIVE" file for the star V Cas. [NOTE: If more than one person or group of people runs the program at the same time over a computer network, make sure each is running in a different subdirectory. If two groups or individuals run the program in the same subdirectory, they will overwrite each other's log files.) Do not load all the available data; when it asks you for the "JD to start," enter 2447000, and when it asks you for the "JD to end," enter 2449000 (this will load 2,000 days of data, from JD 2447000 to 2449000). Look at the light curve; can you tell what kind of variable this is?

Estimating maxima by eye

You will notice that as you move the cursor around the screen, the program constantly displays the cursor location in time (JD) and magnitude. You can conveniently use this display to estimate the times and magnitudes of the maxima of V Cas.

Magnify the time scale so that you have a close-up look at the first maximum in these data. Place the cursor where you believe the maximum is located, both in time and in magnitude. If you hit the "P" key, VSTAR will record the time and magnitude of that point in its log file. VSTAR will also ask if you want to attach a comment to that record; you can just hit <ENTER> (no comment is necessary).

Now change the view so that you have a close-up look at the *next* maximum in these data. Again, place the cursor where you believe the maximum is located, and hit the "P" key, recording this information in your log file. Repeat this procedure for every maximum from JD 2447000 to 2449000. Then exit the VSTAR program.

Now look at the file VSTAR.LOG (the log file created by VSTAR). It should have one line for each maximum, listing the time (JD) and magnitude of your estimate. For example, we found 9 maxima between JD 2447000 and 2449000:

2447125.5172	7.9500
2447351.7242	8.1500
2447571.7241	7.7000
2447795.8621	8.2500
2448020.0000	8.2500
2448228.2759	7.9000
2448473.7931	7.8000
2448692.4138	7.8000
2448921.3793	7.8000

VSTAR records both time and magnitude to the nearest 0.0001, but that is more accuracy than we can expect by eye, so we'll only use times to the nearest 0.01 day, and magnitudes to the nearest tenth.

We can estimate the period as the time from one maximum to the next, so for each maximum (except the first one), take its JD and subtract the JD of the previous maximum. With 9 maxima, this gives us 8 estimates of the period; our estimates are listed in the following table:

JD	Magnitude	Period
2447125.5172	7.9500	
2447351.7242	8.1500	226.21
2447571.7241	7.7000	220.00
2447795.8621	8.2500	224.14
2448020.0000	8.2500	224.14
2448228.2759	7.9000	208.28
2448473.7931	7.8000	245.52
2448692.4138	7.8000	218.62
2448921.3793	7.8000	228.97

Now compute the average period, and the standard deviation. Finally, compute the standard deviation of the average. For our estimates, the average period is 224.48 days, with a standard deviation of 10.58, while the standard deviation of the average is 3.74.

Comparing one time span to another

Now repeat exactly the same procedure as above, with one exception: instead of studying the data from JD 2447000 to 2449000, study the data from JD 2440000 to 2442000. Estimate each maximum, and estimate the periods as the times from each maximum to the next. Compute the average period, the standard deviation, and the standard deviation of the average.

Is the period of V Cas the same from JD 2440000 to 2442000 as it was from JD 2447000 to 2449000?

Yet another way to estimate maxima

Now we will learn yet another way to estimate the time and magnitude of maximum: by fitting a polynomial. Once again, run the VSTAR program. Load the data for V Cas from JD 2447000 to 2449000. Change the view so that you have a close-up of the first maximum; adjust the “view window” so that your screen shows a single cycle of V Cas, starting at minimum, with maximum approximately in the middle of the screen, and ending with the next minimum.

Now hit the <F3> key (fit a polynomial). This instructs VSTAR to fit a smooth curve to the data, a curve of a type known as a *polynomial*. VSTAR will ask you for the polynomial degree, by prompting

```
Polynomial degree = 4
```

Change the “4” to “16” (so we can fit a 16th-degree polynomial), then hit <ENTER>. Now VSTAR will compute a 16th-degree polynomial fit to the data on your screen, and graph that smooth-fit curve as a red line. It will also show you a new menu at the bottom of the screen, the “polynomial menu.”

Now hit the <F5> key (locate MAX/min). VSTAR will ask you to place the cursor near the maximum/minimum you want to identify, then click the left mouse button (or keyboard equivalent). Place the cursor where you believe the maximum lies, then click the mouse button (or keyboard equivalent). VSTAR will compute the maximum or minimum which is closest to your cursor, and plot a blue cross at that location. It will also save the time and magnitude of that point to your log file. Now hit the <ESCape> key; this will take you out of the “polynomial menu” and back to the “main menu.”

Repeat this procedure for every maximum from JD 2447000 to JD 2449000. Isolate each individual cycle (from minimum to minimum, with maximum approximately in the middle), fit a 16th-degree polynomial, and let VSTAR compute the time and magnitude of maximum. When you have finished, exit the VSTAR program.

Now look at the file VSTAR.LOG. It contains a lot of information you do not need, but it also has lines that look like this:

```
2447126.3306     7.8869 = MAX/min
```

This is the VSTAR estimate of the time and magnitude of maximum by polynomial fit. Remove from the file VSTAR.LOG all lines except these, leaving only the MAX/min estimates. We found 9 maxima between JD 2447000 and 2449000:

2447126.3306	7.8869	=	MAX/min
2447352.5845	8.0180	=	MAX/min
2447574.1225	7.6731	=	MAX/min
2447798.9394	8.0078	=	MAX/min
2448019.3119	8.0074	=	MAX/min
2448231.7122	7.8539	=	MAX/min
2448475.3867	7.8820	=	MAX/min
2448694.9989	7.8019	=	MAX/min
2448922.5602	7.6872	=	MAX/min

Again, we can estimate the period as the time from one maximum to the next. So again, we have 8 estimates of the period of V Cas:

JD	Magnitude	Period
2447126.3306	7.8869	
2447352.5845	8.0180	226.2539
2447574.1225	7.6731	221.5380
2447798.9394	8.0078	224.8169
2448019.3119	8.0074	220.3725
2448231.7122	7.8539	212.4003
2448475.3867	7.8820	243.6745
2448694.9989	7.8019	219.6122
2448922.5602	7.6872	227.5613

For each maximum (except the first), take the JD of maximum and subtract the JD of the previous maximum to get an estimate of the period. Compute the average period, the standard deviation, and the standard deviation of the average. For our estimates, the average period is 224.53 days, the standard deviation is 9.07, and the standard deviation of the average is 3.21 days.

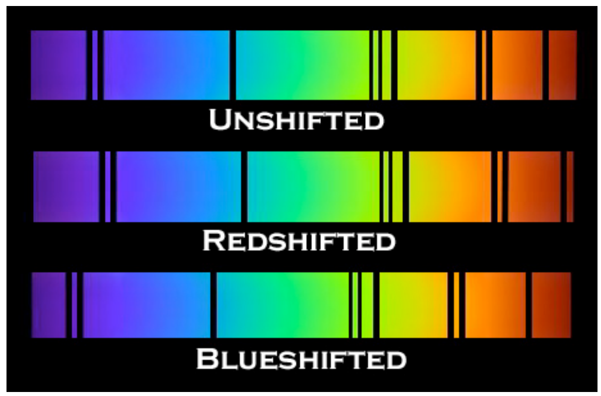
Now repeat exactly the same procedure as above, with one exception: instead of studying the data from JD 2447000 to 2449000, study the data from JD 2440000 to 2442000. Estimate each maximum by fitting a 16th-degree polynomial, and estimate the periods as the times from each maximum to the next. Compute the average period, the standard deviation, and the standard deviation of the average.

Is the period of V Cas the same from JD 2440000 to 2442000 as it was from JD 2447000 to 2449000?

Radar Guns and Speeding Stars

The frequency of a wave as it leaves its stationary source is the same as the frequency of the same wave being detected by an observer. If either the source or observer is moving, however, a perceived change in frequency occurs. We are familiar with the fact that horns and sirens of cars, trains, and ambulances have a higher pitch, or frequency, when they are approaching us, and a lower frequency when they are moving away from us.

The change in apparent frequency, and therefore wavelength, of a wave motion as a result of relative motion of the source and observer is known as the *Doppler effect*, and it works for any source which produces a wavelength, whether it is sound or electromagnetic radiation. As a source emitting a specific frequency moves forward, the wavelengths get "compressed" in front of the source and stretched out behind the source. For electromagnetic radiation emitted from a moving source, the amount of this change is known as the *Doppler shift*.



For a source moving towards the observer, the observed wavelength is shorter than it would be if source and observer had no relative motion along the line joining them. This change to shorter wavelengths, towards the blue end of the visible spectrum, is called a *blueshift*. Conversely, if the source is moving away from the observer, there is a change to longer wavelengths, which is called a *redshift.*

When there is no relative motion between a source and the observer, the wavelength of a spectral line can be given by $\boldsymbol{\lambda}$ (the Greek letter *lambda*). If the relative velocity along the line of sight of source and observer is υ, the change in wavelength $\Delta\lambda$ of the spectral line is given by:

$$\Delta\lambda/\lambda = \upsilon/c$$

where c is the speed of light. For values of upsilon comparable with c, a relativistic expression is used:

$$\Delta\lambda/\lambda = [(c + \upsilon) / (c - \upsilon)]^{1/2} - 1$$

where υ is positive for a receding object and negative for an approaching object. Doppler shifts can be observed in all regions of the electromagnetic spectrum.

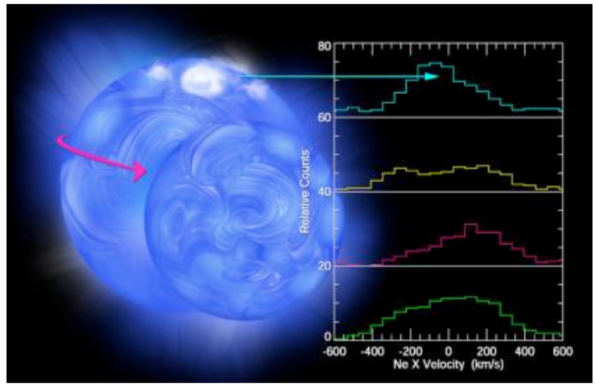
The Doppler effect has proven itself to be invaluable in the field of astronomy. The *radial velocity*, v_r, is the velocity of a star along the line of sight of an observer. It is calculated directly from the Doppler shift in the lines of the star's spectrum. If the star is receding, there will be a redshift in its spectral lines and the radial velocity will be positive. If the star is approaching, its motion will produce a blueshift and the velocity will be negative.

Similarly, the recessional velocities of *galaxies* can be determined from their redshifts. In this case, the emitting source-the galaxy-is moving away from the wavelengths of EMR it is emitting. The wavelengths become stretched out, producing a Doppler redshift in wavelength for observers on Earth. The rate of this expansion for galaxies is related to the age of the universe. Nearby galaxies are moving away from us at speeds of about 250,000 m/s. Distant galaxies are moving away at speeds up to 90% of the speed of light.

The direction that galaxies are rotating can also be determined from Doppler shifts. The part turning towards Earth is blueshifted, and the part turning away is redshifted. The orbital motions of spectroscopic binaries and planetary systems are determined in a similar manner from shifts in spectral lines.

Just as radar guns use the Doppler effect to determine the speeds of moving objects, spectroscopy likewise can tell us the speeds of distant stars and galaxies. Both operate on the same principle of perceived frequency and wavelength changes when emitting sources are moving relative to one another.

This artist's conception depicts the two closely orbiting stars of 44i Bootis. The plots to the right show Chandra data on X-ray emission from Neon ions. The 4 panels show the shift in wavelength at which the Neon X-ray emission peaks as the stars orbit one another. By using the Doppler effect–the same process that causes the frequency of an ambulance's siren to shift up and down as the ambulance approaches and recedes–astronomers were able to pinpoint the location of the source of most of the X-rays.



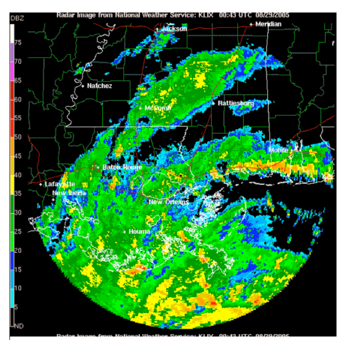
Credit: CXC/M.Weiss

A team of Georgia Tech researchers, including research engineer Francois Guillot in the School of Mechanical Engineering, is developing an inexpensive, handheld device that uses Doppler ultrasound technology to find veins quickly. Georgia Tech Photo: Gary Meek.

Another application of the Doppler effect, besides measuring the expansion of the universe and issuing speeding tickets, is in the medical profession. The Doppler effect forms the basis of a technique used to measure the speed of flow of blood. High-frequency sound waves called ultrasound are directed into an artery. The waves are reflected by red blood cells back to a receiver. The frequency detected at the receiver relative to that emitted by the source indicates the cell's speed. The reflected frequency is combined with some of the sound leaving the source and the combined waves produce a beat frequency which is easily measured, and gives the speed of the flow of the blood in the artery. This helps to determine the location of possible clots or advanced stages of hardening of the arteries. This is a similar arrangement to that used to measure the speed of cars, except that in radar, microwaves are used instead of ultrasound.

Meteorologists also use Doppler radar both in terrestrial and nonterrestrial applications. It is used to measure wind speeds involving severe weather, such as inside tornadoes. It has also helped determine the speeds of the winds on Mars and Venus. Instruments utilizing the Doppler effect are also used to help detect dangerous wind shear at airports.

Sometimes it is surprising how a particular principle is applied or used over a wide range of applications. We are usually unaware of the ways that our lives are affected by principles that we often associate with one specific application. Many of us know that the Doppler effect is associated with radar guns and speeding tickets, but not that it helps measure weather, blood flow, and the age of the universe.

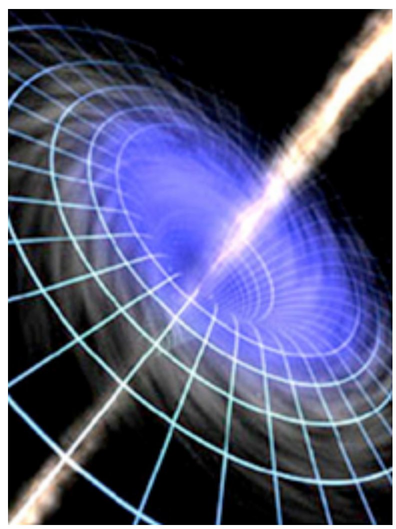


Hurricane Katrina
Doppler Radar
0:43 UTC, 8-29-05

SPACE TALK

DI Herculis, a seemingly ordinary 8th-magnitude binary star 2,000 light-years from Earth, consists of two young blue stars separated by about one-fifth of the Earth-Sun distance. The two stars orbit their common center of mass, or **barycenter**, every 10.55 days. Studies of the DI Herculis eclipsing binary system have uncovered variations that are difficult to explain with either Newton's theory of gravitation or Einstein's theory of relativity. Because we see the system almost edge-on and the stars are small compared to their separation, DI Herculis exhibits very deep and sharp eclipses, and astronomers can make very precise timings. The eclipse times are used to analyze the orbital motions of the system. These motions are extremely puzzling.

According to Newton's theory of gravitation, isolated point particles circling one another will retrace the same paths forever. Real stars, however, are not points. They are big, have internal structure, and rotate. Also, their mutual gravities deform both stars. These departures from perfect symmetry cause the point at which the two stars are closest together, called **periastron**, to rotate about the system's barycenter. In other words, the stars do not retrace the same closed path: they follow an evolving rosette-like orbit, which continuously changes the times of the eclipses. However, the stars are far enough apart so that the gravity from one star does not deform the other into an egg-shaped object. This is important because any significant deviation from a spherical shape magnifies the tidal force and confuses the distinction between Newtonian effects and relativistic ones. DI Herculis' periastron is moving at a rate of 0.65" $\pm$ 0.18" every 100 years. This value is one-third of the expected rate of 1.93" per century, calculated using standard Newtonian physics.



There is an additional contribution to the periastron motion due to the curvature of space predicted by Einstein's **theory of general relativity**. The basic premise of general relativity is that gravitational fields change the geometry of spacetime, causing it to become curved. It is this curvature of spacetime that controls the natural motions of bodies. Matter tells spacetime how to curve and spacetime tells matter how to move. General relativity may therefore be considered as a theory of gravitation; the differences between it and Newtonian gravitation only appear when the gravitational fields become very strong, as with black holes, neutron stars, and white dwarfs, or when very accurate measurements can be made with less-massive objects. When it was formulated by Einstein in 1915, general relativity explained a puzzling anomaly in the behavior of Mercury's orbit. Every planet traces an elliptical path around the Sun. The point where a planet comes closest to the Sun is called **perihelion**. Each planet's perihelion advances slightly from orbit to orbit because the other planets exert gravitational tugs. This **advance of perihelion** means a planet's orbit rotates with time, tracing a rosette pattern over the course of many revolutions. In the mid-1800's, it was obvious that Mercury's perihelion was advancing 43 arcseconds per century faster than Newton's laws predicted. Astronomers postulated that a planet closer to the Sun than Mercury was tugging on its orbit, a planet they named Vulcan. The search for Vulcan went on for years. Then Einstein's theory of general relativity predicted a curvature in the geometry of spacetime around the Sun that would significantly alter the trajectory of nearby Mercury, and the calculation was exactly 43". The mystery of Mercury was explained, and the search for Vulcan was discontinued.

The additional contribution to the periastron motion due to the curvature of space, predicted by the equations of general relativity for DI Herculis, amounts to a relativistic effect of 2° 34" for every 100 years. The net result is that the observed change is seven times smaller than was predicted using prevailing theoretical models. The discrepancy between observation and theory is well determined by several studies, and there is no problem with the observational data. Einstein's theory of gravity has passed previous observational tests with flying colors. However, there are a number of double stars for which it does not seem to work. DI Her should have provided an excellent test for general relativity in a strong gravitational field. DI Her's stars are massive enough (4.5 and 5.2 solar masses) and close enough that they significantly curve the spacetime around each other. The curvature should cause the system's **line of apsides**, the longest axis of the elliptical orbit, to advance 200 times faster than the Sun causes Mercury's perihelion to advance.

The possible causes for the discrepancy in **apsidal motion**—such as a third hidden star, tipped rotation axes, messy internal structures for the DI Her stars, unusual magnetic fields and extreme stellar winds—have all been ruled out. There is no evidence for orbital perturbation; the spectra show an upright orientation; no magnetic fields have been detected; and the observed winds are weak. DI Her is a mystery. No one is willing to abandon general relativity because it has more than proven itself. However, there may well be an addendum to the theory. One possibility is that spacetime has higher dimensions. General relativity works in four dimensions, but extending the theory to include five or more dimensions may explain why the periastron advance of DI Her is much less than expected.

Chapter 11: Variable Stars, Light Curves, and Periodicity

Summary

The graph of the apparent brightness (magnitude) of a variable star versus time (Julian Day or JD) is called a light curve. It is the most important graph in variable star astronomy. This chapter is an introduction to the peculiarities of light curves, and how to plot and interpret them. The period of a variable star can be calculated from the light curve, by determining the times of maxima and minima.

Terminology

apsidal motion	Mira variables	RR Lyrae stars
barycenter	nebulosity	RV Tauri stars
cycle	novae	semiregular variables
dwarf novae	periastron	superhumps
envelope	perihelion	superoutburst
eruptive variables	period	supernovae
general relativity	Pogson's method of bisected chords	SU Ursae Majoris stars
light curves	precession of the perihelion	symbiotic stars
line of apsides	pulsating variables	T Tauri stars
maximum, maxima	R Coronae Borealis stars	U Geminorum Stars
minimum, minima	recurrent novae	variable stars

SUGGESTIONS FOR POSTER PAGES, INVESTIGATIONS, AND ACTIVITIES

Investigation 11.1: Recognizing Periodic Curves

VSA VIDEO

The students are given several curves and given the task of identifying which ones are periodic. All the curves are actual curves from various types of variable stars. Some of the curves are obviously periodic, others are less obvious, and some do not have any obvious periodicity. At this point, it would be helpful to show the students the "Variable Stars" part of the HOA video, which explains the different types of variable stars and their natures. After students have chosen periodic curves and calculated their periods, they can use the summary of the different types of variable stars—included in both the Appendix and in the Chapter 11 introduction— to determine which types of variables are producing the different curves. Let them know that all of the light curves belong to different kinds of variable stars in the AAVSO International Database. While all variables vary in magnitude, not all variables are obviously periodic. You will note that (c) and (d) are the same types of variable, as are (e) and (f), etc., so that students can compare their light curves and easily see that even two of the same type of variable star can have very different light curves. Variables (a) and (b) have no obvious periodicity.

Note: Remember, you find the maximum and minimum magnitudes and period by looking at many cycles and taking the averages.

Answer Key (answers based on data shown in printed light curves on pages 192–194)

(a) R CrB
Maximum magnitude: 6.0
Minimum magnitude: 13.8
Period: No specific period
Type: R Coronae Borealis (RCB)

(b) RS Oph
Maximum magnitude: 5.3
Minimum magnitude: 12.3
Period: No specific period
Type: Recurrent Nova (NR)

(c) Chi Cyg
Maximum magnitude: 5.2
Minimum magnitude: 13.8
Period: 408 days
Type: Mira (M)

(d) S UMa
Maximum magnitude: 7.8
Minimum magnitude: 11.7
Period: 225.9 days
Type: Mira (M)

(e) W Cyg
Maximum magnitude: 5.6
Minimum magnitude: 6.8
Period: Star has more than one period
Type: Semiregular (SR)

(f) Z UMa
Maximum magnitude: 6.8
Minimum magnitude: 8.7
Period: Star has more than one period
Type: Semiregular (SR)

(g) Z Cam
Maximum magnitude: 10.5
Minimum magnitude: 13.2
Period: 22 days
Type: Z Camelopardalis (Z Cam)

(h) SS Cyg
Maximum magnitude: 8.2
Minimum magnitude: 12.2
Period: 49.5 days
Type: U Geminorum (UG)

(i) CH Cyg
Maximum magnitude: 5.8
Minimum magnitude: 9.2
Period: Star has more than one period
Type: Z Andromedae (Z And)

(j) X Cyg
Maximum magnitude: 6.0
Minimum magnitude: 7.0
Period: 16.4 days
Type: Cepheid (C)

Poster Page: Mapping the Universe (HIPPARCOS)

The history of astrometry is a good example of how technology drives knowledge. A lot of time and money are spent on mapping the positions of stars. It may not seem very important to students—after all, at this point all distances are almost incomprehensibly far away, so who cares if a star is 35 or 100 light-years away? Distance is one of the key factors in the equation called the distance modulus, discussed in Chapter 9. It is related to apparent and absolute magnitude. Absolute magnitude is related to the luminosity or power of a star. Knowing the luminosity gives us a lot of information about the evolutionary stage of a star, its physical characteristics, and its behavior. This knowledge has implications for the age of the universe and its ultimate fate, as well as for origins of life. Another generation of astrometric measuring satellites is already on the drawing board, even before the full implications of the HIPPARCOS data have been analyzed. The amazing fact is that we are able to map the universe from the Earth's own backyard.

Core Activity 11.2: Analyzing the Light Curve for Star X

The students will plot both their individual data sets (part A) and the class average data set (part B). They should see that the data are less scattered and the error is smaller for larger sets of data. Using the maxima and/or minima, they can calculate the period of Star X. Again, there is no exact or correct answer. The answer is what they get. They will also use the standard error of the average which they calculated and recorded in the previous chapter (Table 10.4, column [H]). The graph might get cluttered, since they will include the error bars and draw the envelope for both data sets. However, the best way to compare the error analysis of the two sets of data is to plot both of them on the same graph. Then the widths of the two envelopes are more apparent. You may elect to have one or both of the data sets transferred to transparencies to use as overlays on an overhead projector.

Core Activity 11.3: Analyzing the Light Curve for Delta Cephei

Hopefully there are some classroom data for observations of delta Cep. The students can then compare the analysis of their own observations with Star X. Even though the periods are different, they can compare the error bars and size of the envelope to get a feel for the precision of their observations and the accuracy of their results. Reinforce with your students that even though they are observing a variable star for which the period is known, the periods for new variables are not known, and variables often change their periods. Therefore it is essential to have results as accurate as possible because there is no "right" answer to compare the results with. Remind the students that if they want to compare their results (width of error bars and the envelope) from Star X with their results for delta Cep, they have to use the same size scale for the two graphs.

Core Activity 11.4: Pogson's Method of Bisected Chords

You may want to point out to your students that once again, averaging is taking place in this method of determining the maxima and minima points of a light curve. The entire curve involving maximum is taken into account, not just the high point in the curve. (The same is true for the minimum.) Therefore many observations and not just the two highest and lowest are being used for the analysis, giving more accuracy to the determination of the period.

Core Activity 11.5: VSTAR

VSTAR

Now that the students have a basic understanding of the statistical analyses involved with determining the periods of variable stars, they can use the VSTAR program. A VSTAR manual is included in the Appendix which will explain the program to the students. The first VSTAR activity is self-explanatory, and if the students have any questions, they can consult the VSTAR manual. **NOTE: If more than one student (or group of students) runs the program at the same time over a computer network, make sure each is running in a different subdirectory. If two groups run the program in the same subdirectory, they will overwrite each other's log files.**

Students can access the database for observational data and use the statistical package within the program to plot light curves, error bars, and envelopes. If they have delta Cep observational data, have them enter them into the program and determine the light curve, period, error bars, and envelope, and compare the results with their own calculations. They cannot add their observations to the database on this software package, but can enter their observations for analysis.

Poster Page: Radar Guns and Speeding Stars

Radar is an extremely useful tool to gather information, astronomical or otherwise. Exactly how does a radar gun work? How are winds measured on other planets using the Doppler effect? Students seldom understand how physical laws and principles impact their lives. When they do, they begin to understand that things that work seemingly like magic are only the application of very simple phenomena. Doppler is useful in many circumstances, and research into this area will probably turn up some surprises. When did Doppler discover this effect? How was it first used? How long did it take before it was employed by police to trap speeders? Do radar guns work from the front, the side, the back? Just how do radar detectors detect radar guns? Can both radar guns and radar detectors give inaccurate readings? There are other types of radar than Doppler radar. In meteorology and at airports, Doppler maps are used to determine wind speed and direction. Profiles from the ocean bottom are the result of the reflection of sound waves back from the ocean floor. With this type of radar, the difference in time is recorded. There is no change in frequency.

Chapter 12: Variable Stars and Phase Diagrams

Introduction

When the same cycle repeats over and over as regularly as clockwork, we refer to this as *periodic* behavior. If we want to know what is happening at any moment, it does not matter which cycle we are observing, because every cycle is exactly the same. What does matter is which *part* of the cycle we are observing. So if a star (or any other phenomenon) is perfectly periodic, then its variation depends only on where it is in its cycle, a quantity called the *phase*.

A good example is an accurate clock. If it is a 24-hour clock (with an AM/PM indicator), it repeats exactly the same behavior, over and over, with a period of 1 day. Each day the clock goes through one cycle, and each cycle is just like every other cycle. If we want to know what the clock reads, we do not need to know which day it is (which cycle it is in), we just need to know the time of day (how far we are into the cycle).

Phase in Cycles

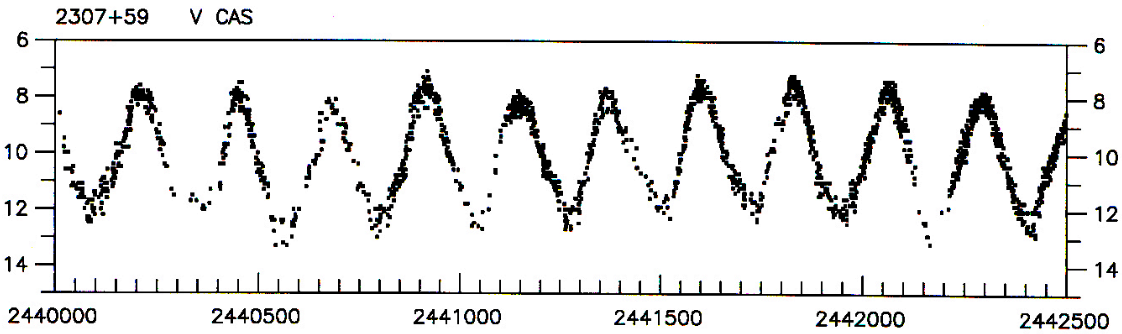
In the case of the clock, we might measure "how far into the cycle" it is in terms of hours and minutes, with the cycle starting at 00:00 and ending at 24:00. Of course, 24:00 (the end of the cycle) is also 00:00 on the *next day*, because the end of one cycle coincides with the beginning of a new one.

However, phase is measured in *cycles*, rather than in hours or minutes. Since phase is measured in cycles, of course a single cycle starts at 0 and ends at 1. In this case, the phase is simply the fraction of the cycle which has been completed so far. Thus a phase of 0.5 corresponds to 0.5 of the way (50%, or halfway) through the cycle, a phase of 0.2 is 20% (one-fifth) of the way through the cycle, etc. A phase of 1 is 100% of the way, the end of the cycle; it is also the beginning of the *next* cycle, so it is phase 0 of the next cycle.

To compute the phase in terms of cycles, we need to know how long each cycle is—in other words, we need to know what the *period* is. For the clock, we can express the phase in hours and minutes. But to express the phase in terms of cycles, we need to know that each cycle (each day) is 24 hours. That way, at noon, when we are 12 hours into the cycle, we know we are 12/24 = 0.5 of the way through, meaning that the phase is 0.5.

Investigation 12.1: Periodic Cycles

Cycles have no real beginning and no real end—they are continuous. Study the continuous light curve for V Cas on the opposite page. Cut out the sections and tape them together to see the behavior of V Cas from JD 2440000 to JD 2450000. If you use just two sections, do you still have a representation of the star's behavior? With just one section? Your instructor will give you a transparency of the same light curve. Can you cut the sections in any place and still have the same behavior pattern? Stack several sections over each other. Determine how small a segment is needed to give the same information and all four segments. What if you only had one cycle of the light curve? What if you start your cycle at maximum? Minimum? Describe your results.


2307+59 V CAS
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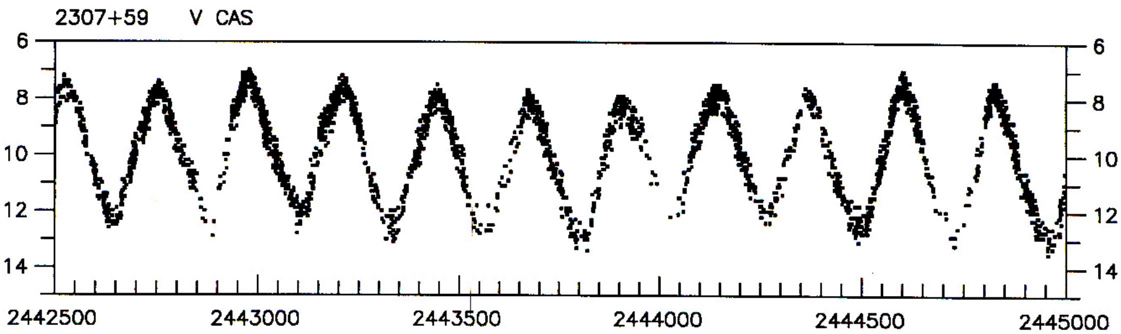
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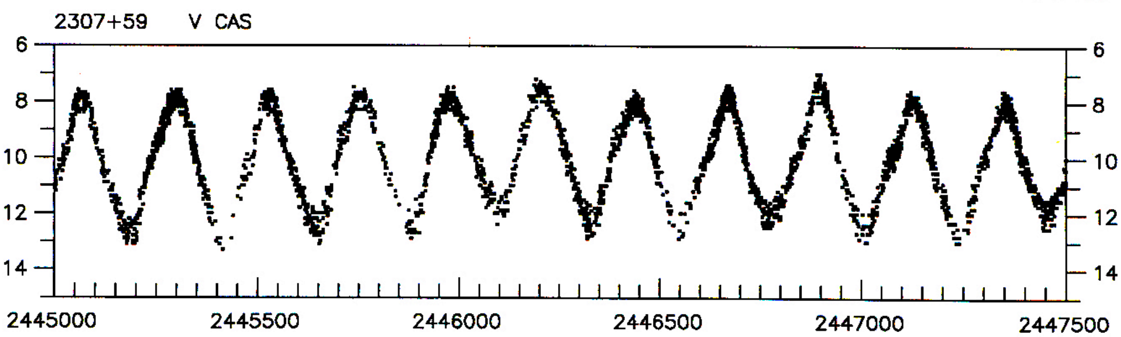
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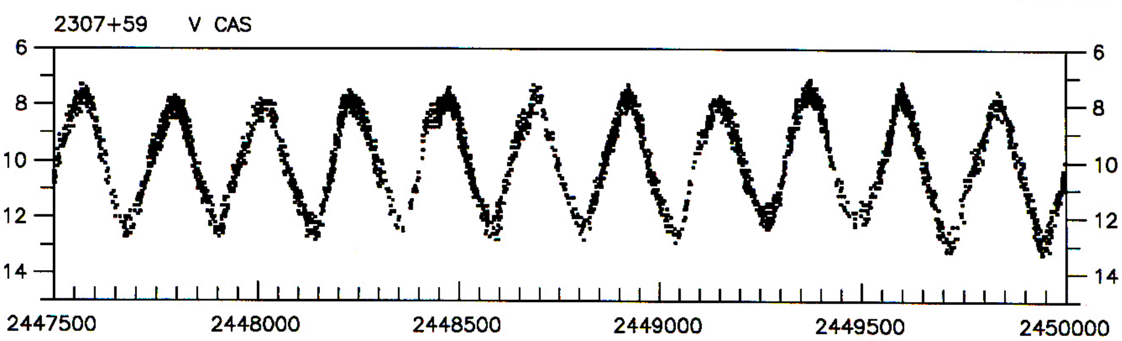
2307+59 V CAS
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2450000

A New Beginning

The clock cycle starts at midnight, because timekeepers have chosen to start each new day at midnight. But this is an arbitrary choice. Other cultures start a new day at sunrise or sunset, rather than at midnight. If the day (the cycle) starts at sunrise (say, 6:00 AM), then we are *not* halfway through the cycle at noon (12:00), so the phase is *not* 0.5. We may have 12 hours on the clock, but because we agree that our cycle *starts* at 6, we are only 12 - 6 = 6 hours into the cycle. That is 6/24 = 0.25 of the cycle (25%, or one fourth), so the phase is 0.25. Therefore, to compute phase we *also* need to know the starting time of the cycle. This is known as the *epoch*. For the clock, the epoch is usually midnight, but some people prefer to start their cycles at some other time.

These two quantities, the *period* and *epoch*, enable us to compute the *phase* at any given time. Suppose the epoch (start of the cycle) is at time t_0, and the period is P. What is the phase at some other time t? First we find how far we are into the cycle, by simply subtracting the starting time:

$$t - t_0$$

This is the phase, in *time* units. To get the phase in units of cycles, we simply divide this by the period:

$$\phi = \frac{t - t_0}{P}$$

The symbol ϕ is the Greek letter "phi," which is used to represent the phase (in cycles). In the case of the clock, with the cycle starting at 6 AM, the period is $P = 24$ (hours) and the epoch is $t_0 = 6$. At noon ($t = 12$), the phase is:

$$\phi = \frac{t - t_0}{P} = \frac{12 - 6}{24} = \frac{6}{24} = 0.25$$

0 = 1 (yes, zero equals one)

Let's go back to starting each new day at midnight, so for our clock the period is P = 24 12) the phase is 0.5 (halfway), and at the following midnight (t = 24) the phase is 1 (end of the cycle). What about the *following* noon?

In this case the time is t = 36; it has been 36 hours since our "epoch." The phase is:

$$\phi = \frac{36 - 0}{24} = 1.5$$

But something is not right here. We said that phase was "how far along we are in the cycle," and that it did not matter which cycle, so it should be the same, every noon. But this phase (ϕ = 1.5) is *not* the same as that of the previous noon (ϕ = 0.5).

Or is it? We could say that ϕ = 1.5 is "one-and-a-half cycles," or we could say that it is "halfway through the *next* cycle." Since we are not interested in which cycle, we ignore the "next" part, and say "halfway"; thus the phase is 0.5.

In fact, whenever we compute a phase, we can make it into a "standard" phase by simply *ignoring* which cycle. If the phase is ϕ = 3.11 (a little more than three cycles), we are 11% of the way through *three cycles later*. We will ignore the "three cycles later" part, note that we are 11% of the way through a cycle, and say the phase is 0.11. All *standard* phases are between 0 and 1.

When phase is expressed in cycles, it is easy to identify which cycle: it is just the *integer* part of the phase, or cycle number. For a phase ϕ = 3.11, the integer part (3) tells us that we are dealing with cycle 3, and 0.11 of 3.11 tells us we are partway through cycle 3. Since a standard phase ignores this, we can simply ignore the integer part of the phase (telling us which cycle). What really counts is the *decimal* part of the phase (how far into the cycle). So we will modify the above equation, and say that the (standardized) *phase* is the decimal part of what we had before:

$$\phi = \text{decimal part of } \left[\frac{t - t_0}{P}\right]$$

What this means is that a phase of 1 (start of next cycle) is really the same as a phase of 0 (start of this cycle) or a phase of 3, or 17, or 256. Any two phases which differ by an integer are really the same phase. Phase 1.5 is the same as phase 0.5, phase 12.336 is the same as phase 0.336, and yes, 0 = 1.

This may seem strange, but it is actually mathematically sound. We are simply taking all numbers *modulo 1*. We can still do arithmetic, still compute numbers, but we always ignore the integer part of whatever we end up with. This kind of arithmetic is known as *modular arithmetic*. In modular arithmetic, modulo 1, we can quite validly state the following equation:

$$0 = 1 = 2 = 3 = 4 = ...$$

Negative Phases

One thing to be careful of is *negative* phases. For the clock example (P = 24 and t_o = 0), let us compute the phase at 6 AM three days *previously*. In this case the time is t = -66 (it is 66 hours before our epoch), so the phase is:

$$\phi = \frac{-66 - 0}{24} = -2.75$$

To convert this to a standard phase, we cannot "just ignore" the –2 and call it 0.75. If we did that, we would also be ignoring the minus sign. So we will just remember that we are doing arithmetic modulo 1, which allows us to add or subtract *any* integer without really changing the result. Let us add 3: ϕ = –2.75 + 3.00 = 0.25. This does fall in the range 0 to 1, so this is the standard phase.

Folded Light Curves

Take a look at the following light curve of the Cepheid-type variable X Cyg (Figure 12.1). All observations were made by AAVSO observer LX. There are enough data that we can see an up-and-down variation, which turns out to be periodic with a period of 16.285 days. Still, there are only a few observations for each cycle, so it is difficult to tell exactly what the *shape* of a cycle is.

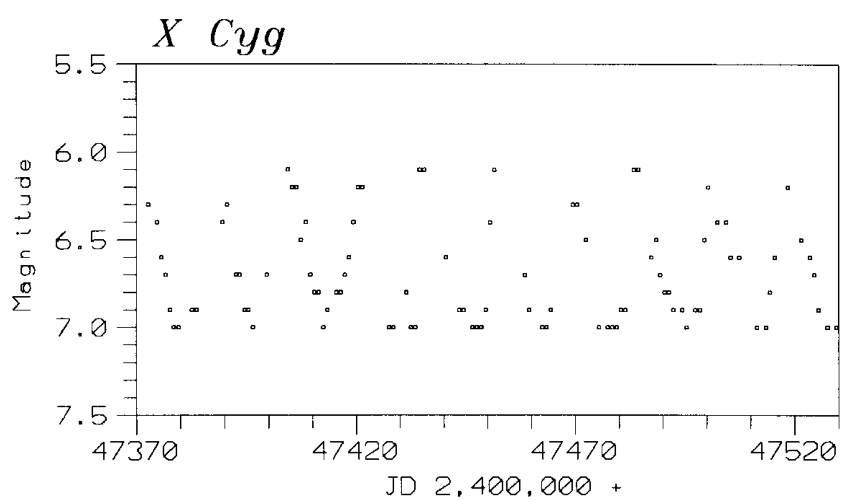


Figure 12.1

It would be nice if we could superimpose all the cycles on top of each other. We would like to plot each data point, but instead of plotting the time, we would like to plot "how far it is into the cycle." That way, all the cycles will be "folded" on top of each other, and we may have enough data to give us an accurate picture of what the cycle looks like. We already have a name for "how far into the cycle": we call it the *phase*. For a variable star, we can do exactly the same thing we did with the clock. Find the period P, choose an epoch t_0, and we can compute the standard phase for any time t. Then we can plot a light curve, but instead of plotting magnitude as a function of *time*, we will plot magnitude as a function of *phase*. This will give us what is called a *folded light curve,* or *phase diagram.*

Let's use the period 16.285 days, and choose as a starting point JD 2,447,400 (an arbitrary choice). Then we can take each observation and convert the time into phase. Plotting brightness as a function of phase, we have the following folded light curve (Figure 12.2):

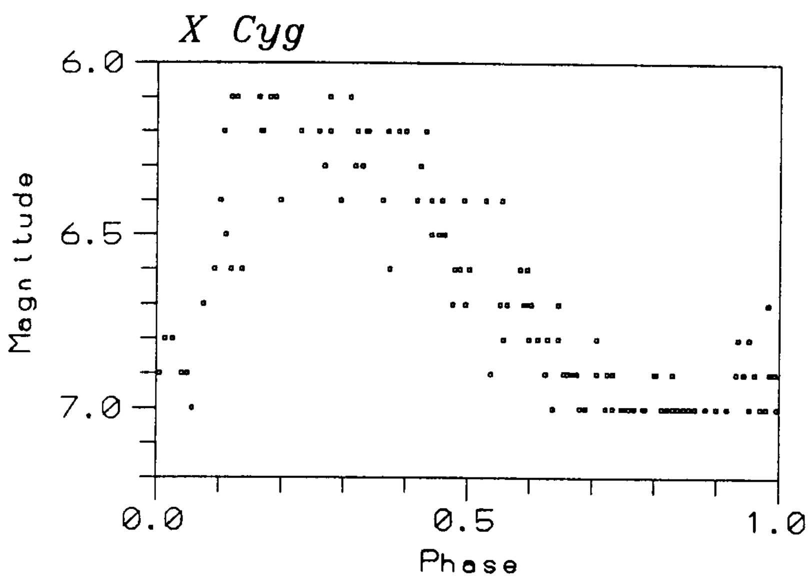


Figure 12.2

Now we *can* see what the shape of the cycle is. There is a very rapid rise from minimum to maximum, followed by a much slower decline from maximum to minimum.

Core Activity 12.2: Folded Light Curve of the Variable Star SV Vul

You are now ready to construct a folded light curve, or phase diagram, using the observations of a Cepheid variable given in the following table.

Table 12.1
SV Vul Magnitude Measurements (1987–1989)

Julian Date	Mag.	Julian Date	Mag.
2447011.6	7.0	2447458.5	6.9
2447023.6	7.5	2447475.5	7.8
2447040.6	7.9	2447492.5	7.9
2447066.5	7.4	2447505.5	7.2
2447091.4	7.0	2447529.5	7.9
2447103.6	7.2	2447707.6	7.9
2447124.6	7.8	2447722.6	6.7
2447171.5	7.9	2447747.6	7.8
2447308.6	7.9	2447769.5	6.8
2447338.6	7.8	2447778.5	7.1
2447374.6	7.0	2447800.5	7.9
2447390.6	7.9	447821.6	7.0
2447404.5	7.8	2447832.5	7.5
2447413.5	6.8	2447848.5	7.9
2447421.5	7.2	2447857.4	6.8
2447444.5	7.9	2447868.5	7.2

1. Construct a graph with the magnitude on the vertical axis and phase on the horizontal axis. Determine the appropriate magnitude scale from the data in Table 12.1. Since all standard phases are between 0 and 1, choose a scale for the phase axis which goes from 0 to 1.

2. We defined the phase as the decimal part of [$(t–t_o)/P$], where t_o is the epoch and P is the period. Take the JD of the very first observation as the epoch, so t_o = 2447011.6. Then the first observation occurs at the start of the cycle (we chose our epoch that way), so we already know the phase of the first observation: it is at phase 0 (start of the cycle). The magnitude of the first observation is 7.0, so plot a point on your graph at phase 0 and magnitude 7.0.

3. For all the other observations, we apply our formula for computing phase. First we take the time of the observation and subtract the epoch time t_0. For the 2nd data point, this gives

   $$\begin{array}{ll} 2447023.6 & \text{(time of observation } t\text{)} \\ \underline{-\ 2447011.6} & \text{(time of epoch } t_0\text{)} \\ 12.0 & \text{(time difference)} \end{array}$$

   Then we divide by the period P. For SV Vul, the period is $P = 44.8$ days. This gives

   $$12.0 / 44.8 = 0.2679$$

   Then we take the decimal part of what we get. Since this result is already between 0 and 1, it is already a standard phase. So for observation #2, the phase turns out to be 0.2679. For plotting purposes, we can round this off to 0.27.

   Repeat this process for every data point, computing the standard phase. When you have computed all the phases, plot each data point at the correct phase and magnitude.

4. Draw a smooth curve showing the trend of the data. Do most of the data lie near this smooth curve? This is a test of the period. Lots of scatter with no obvious trend would show that the measured period is not correct. The correct period should produce a phase diagram whose scatter is about the same as the scatter in the raw data (usually about 0.2 magnitude).

Double Your Fun

Look again at the folded light curve of X Cyg (Figure 12.2). It is a little difficult to see the behavior near minimum, because the picture is "broken" at phase 0 = 1, leaving a gap in the graph. It would be nice if we had a clear picture of the entire cycle, with no breaks.

We can, if we use the fact that phase is a modular quantity, modulo 1. So a phase of 0 is the same as a phase of 1, and the same as a phase of -1. A phase of 0.133 is the same as a phase of 0.133 – 1 = -0.867. A phase of 0.58 is the same as 0.58 - 1 = -0.42. For each time, let us compute not just one phase, but *two* phases. We will compute the standard phase, which is always between 0 and 1, and we will also compute the "previous cycle phase (ϕ')," which will be between -1 and 0. If the standard phase is ϕ, then the "previous cycle phase" is $\phi' = \phi - 1$.

Note that this "previous-cycle phase" will end up being negative. We already learned how to change a negative phase into a standard phase. Now we are changing a standard phase into a negative phase! But not just any negative phase will do. A proper "previous-cycle phase" has to fall in the range of -1 to 0, just as a proper "standard phase" must fall in the range 0 to 1. It is easy to compute, if you just remember to take the standard phase and subtract 1 to give the proper "previous-cycle" phase. **Always compute the standard phase first, then subtract 1 to get the previous-cycle phase.**

We will plot magnitude as a function of phase, but we will plot each data point at *both phases*, the standard phase and the "previous-cycle" phase. In effect, we will be plotting each data point *twice*, and since our phases now run from -1 to +1, we will have a nice picture of not one, but *two* complete cycles. Now it is easy to see what the star is doing at any point of its cycle, because we have an unbroken graph (Figure 12.3):

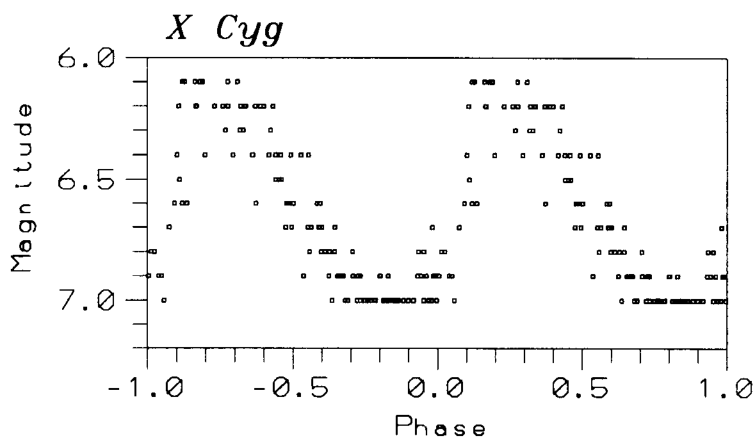


Figure 12.3

When astronomers plot folded light curves, they almost always plot two complete cycles, with phase extending from -1 to +1, in order to give a clear picture of the shape of the entire cycle.

Core Activity 12.3: Another Folded Light Curve of SV Vul

Table 12.1
SV Vul Magnitude Measurements (1987–1989)

Julian Date	Mag.	Julian Date	Mag.
2447011.6	7.0	2447458.5	6.9
2447023.6	7.5	2447475.5	7.8
2447040.6	7.9	2447492.5	7.9
2447066.5	7.4	2447505.5	7.2
2447091.4	7.0	2447529.5	7.9
2447103.6	7.2	2447707.6	7.9
2447124.6	7.8	2447722.6	6.7
2447171.5	7.9	2447747.6	7.8
2447308.6	7.9	2447769.5	6.8
2447338.6	7.8	2447778.5	7.1
2447374.6	7.0	2447800.5	7.9
2447390.6	7.9	447821.6	7.0
2447404.5	7.8	2447832.5	7.5
2447413.5	6.8	2447848.5	7.9
2447421.5	7.2	2447857.4	6.8
2447444.5	7.9	2447868.5	7.2

You are now ready to construct a second phase diagram of SV Vul, this time computing two phases for each point, and plotting a folded light curve showing two complete cycles.

1. Construct a graph with magnitude on the vertical axis and phase on the horizontal axis. Determine the appropriate magnitude scale from the data in Table 12.1. Since we will be plotting two cycles in our folded light curve, our phases will run from -1 to +1. Choose a scale for the phase axis which goes from -1 to 1.

2. We defined the phase as the decimal part of [$(t-t_o)/P$], where t_o is the epoch and P is the period. Take the JD of the very first observation as the epoch, so t_o =2447011.6. Then the first observation occurs at the start of the cycle (we chose our epoch that way), so we already know the phase of the first observation: it is at phase 0 (start of the cycle). The magnitude of the first observation is 7.0, so plot a point on your graph at phase 0 and magnitude 7.0.

3. For all the other observations, we apply our formula for computing phase. First we take the time of the observation and subtract the epoch time t_0. For the 2nd data point, this gives

$$\begin{array}{rl} 2447023.6 & \text{(time of observation } t\text{)} \\ \underline{-\ 2447011.6} & \text{(time of epoch } t_0\text{)} \\ 12.0 & \text{(time difference)} \end{array}$$

   Then we divide by the period P. For SV Vul, the period is $P = 44.8$ days. This gives

   $12.0 / 44.8 = 0.2679$

   Finally, we take the decimal part of what we get. Since this result is already between 0 and 1, it is already a standard phase. So for observation #2, the phase turns out to be 0.2679. For plotting purposes, we can round this off to 0.27.

   Repeat this process for every data point, computing the standard phase for each data point.

4. Now compute the "previous cycle phase" for each data point. To do so, simply take the "standard phase" you just computed, and subtract 1. You now have two phases for each data point, a standard phase between 0 and 1, and a previous-cycle phase between -1 and 0.

5. Plot each data point at its correct magnitude, and at *both* phases (so each observation gives two points on the graph).

6. Draw a smooth curve showing the trend of the data. You should be able to discern two complete cycles of variation in the graphs. Do most of the data lie near this smooth curve? This is a test of the period. Lots of scatter with no obvious trend would show that the measured period is not correct. The correct period should produce a phase diagram whose scatter is about the same as the scatter in the raw data (usually about 0.2 magnitude).

Start from the Top

For X Cyg in Figure 12.1, we chose as our epoch, or starting point, JD 2,447,400, just because it was convenient. However, astronomers prefer to choose an epoch so that the *maximum occurs at phase zero*. So let us take as our epoch the time of one of the maxima, JD 2,447,403.0. Then our folded light curve has its maximum right at phase 0 (Figure 12.4):

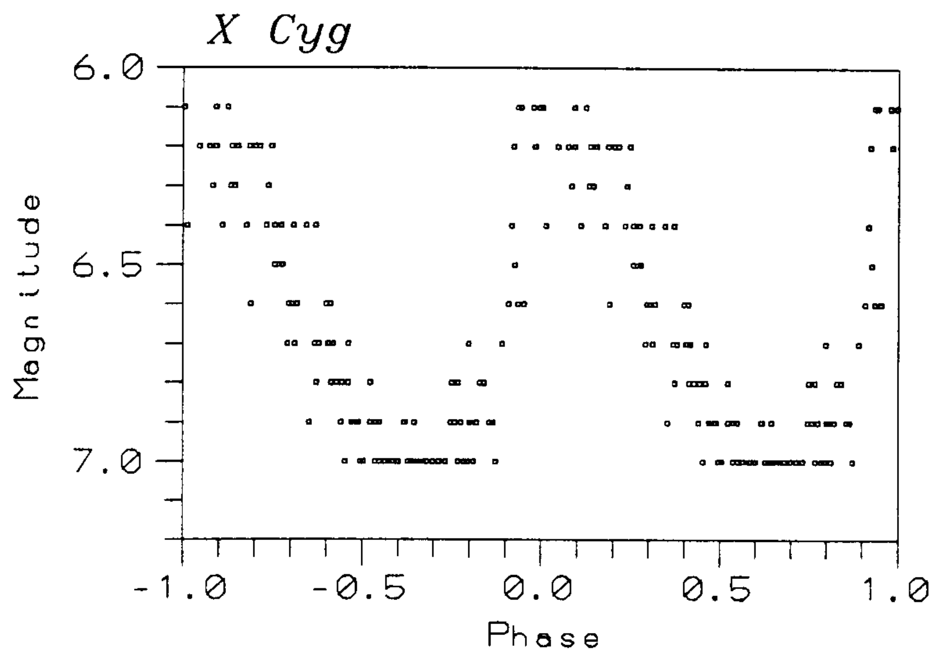


Figure 12.4

This is the *standard folded light curve* for a variable star. It plots two complete cycles, with phase running from –1 to +1, and the epoch is chosen so that maximum occurs at phase zero.

There is one exception to this rule: eclipsing binary stars. For eclipsing binaries, the *minimum* brightness (which usually occurs in the middle of the eclipse) is the part we are really interested in, so we choose the epoch so that phase zero is *minimum* rather than maximum.

Core Activity 12.4: Yet Another Folded Light Curve of SV Vul

Table 12.1
SV Vul Magnitude Measurements (1987–1989)

Julian Date	Mag.	Julian Date	Mag.
2447011.6	7.0	2447458.5	6.9
2447023.6	7.5	2447475.5	7.8
2447040.6	7.9	2447492.5	7.9
2447066.5	7.4	2447505.5	7.2
2447091.4	7.0	2447529.5	7.9
2447103.6	7.2	2447707.6	7.9
2447124.6	7.8	2447722.6	6.7
2447171.5	7.9	2447747.6	7.8
2447308.6	7.9	2447769.5	6.8
2447338.6	7.8	2447778.5	7.1
2447374.6	7.0	2447800.5	7.9
2447390.6	7.9	447821.6	7.0
2447404.5	7.8	2447832.5	7.5
2447413.5	6.8	2447848.5	7.9
2447421.5	7.2	2447857.4	6.8
2447444.5	7.9	2447868.5	7.2

You are now ready to construct a "standard" phase diagram. Estimate the maximum by inspecting the data in Table 12.1, and choose an epoch so that the maximum occurs at phase 0.

1. Construct a graph with magnitude on the vertical axis and phase on the horizontal axis. Determine the appropriate magnitude scale from the data in Table 12.1. Since we will be plotting two cycles in our folded light curve, our phases will run from –1 to +1. Choose a scale for the phase axis which goes from –1 to 1.

2. We defined the phase as the decimal part of $[(t-t_o)/P]$, where t_o is the epoch and P is the period. The brightest of all the observations is the estimated magnitude of 6.7 on JD 2447722.6. Take this as a rough estimate of the time of maximum, and use it as your epoch: t_o = 2447722.6.

3. For each observation, apply the formula for computing phase. First we take the time of the observation and subtract the epoch time *t0*. For the 1st data point, this gives

2447011.6	(time of observation *t*)
– 2447722.6	(time of epoch *t0*)
-711.0	(time difference)

Then we divide by the period *P*. For SV Vul, the period is $P = 44.8$ days. This gives

- 711 / 44.8 = -15.8705

Finally, we take the decimal part of what we obtain. Since this result is negative, we remember to add an integer to make the sum fall between 0 and 1. Adding 16, we get the standard phase as $\phi = 0.1295$. Repeat this process for every data point, computing the standard phase.

4. Now compute the "previous cycle phase" for each data point. To do so, simply take the "standard phase" you just computed, and subtract 1. You now have two phases for each data point, a standard phase between 0 and 1, and a previous-cycle phase between –1 and 0.

5. Plot each data point at its correct magnitude, and at *both* phases (so each observation gives two points on the graph). This is the standard folded light curve.

6. Draw a smooth curve showing the trend of the data. You should be able to discern two complete cycles of variation in the graphs. Does the maximum lie at phase 0? This is a test of the epoch; if the maximum is noticeably different from phase 0, then the epoch is not quite correct. Do most of the data lie near this smooth curve? This is a test of the period. Lots of scatter with no obvious trend would show that the measured period is not correct. The correct period should produce a phase diagram whose scatter is about the same as the scatter in the raw data (usually about 0.2 magnitude).

The Discovery of SS Cygni

(Adapted from a paper entitled "The Centennial of the Discovery of SS Cygni " by Martha L. Hazen, published in the Journal of the AAVSO*, Volume 26, 1997, pp. 59–61. Dr. Hazen is the Curator of Astronomical Photographs at Harvard College Observatory. Additional information about SS Cygni was provided by the technical staff of the AAVSO.)*

In the *Harvard College Observatory Circular* No. 12, signed by Edward C. Pickering and dated November 2, 1896, there appeared a listing entitled "New Variable Stars in Crux and Cygnus." The last paragraph of the listing reads:

> In addition to the above objects a star in the constellation Cygnus, whose approximate position for 1900 is R.A. = $21^h38^m.8$, Dec. $+43^o8$ has been found to be variable by Miss Louisa D. Wells. Its period appears to be about 40 days and its photographic brightness varies from 7.2 to fainter than 11.2, an unusually large range for a variable having so short a period.

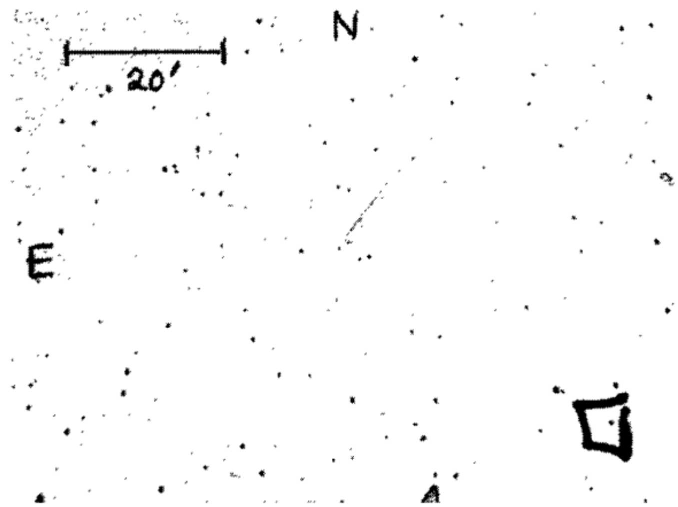


Figure I a. SS Cygni near minimum.

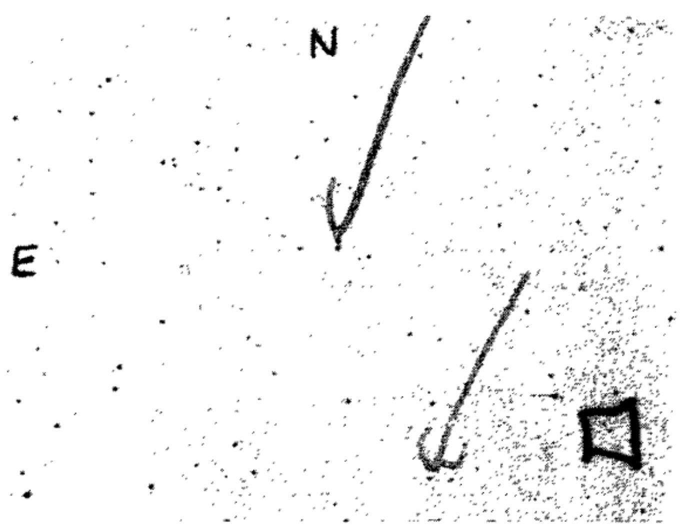


Figure 1 b. SS Cygni in outburst.

Miss Louisa D. Wells was one of the women "computers" hired by E.C. Pickering to work with the Harvard photographic plates. All the original research notebooks kept by the "computers" are stored at the Harvard University Deposit Library, and a complete list of the notebooks is available at the Plate Stacks of the Harvard Observatory. Curiously, Miss Wells's notebooks, necessary for her work, are not in the collection. Her supervisor at the time made no mention of the discovery.

The earliest plate intentionally taken of SS Cyg is plate I 15990, taken with the 8-inch Draper refractor located on the grounds of the Observatory in Cambridge, MA. The plate was taken on September 23, 1896, according to the record book. The entry in the "Object" column says "Susp. var." and the first word is crossed out and "L.D. W.'s" written above.

The earliest plate still extant was taken on September 24, 1890 (see Figure I a; a hand drawn arrow points to SS Cyg in roughly the center of the photo), when SS Cyg was at or near minimum. Figure 1 b is a plate taken on October 30,1890, when the star was in outburst.

The complete details of the discovery of SS Cyg may never be known, but with its discovery began a long period of visual observations so complete that an outburst of this well-studied star has never been missed.

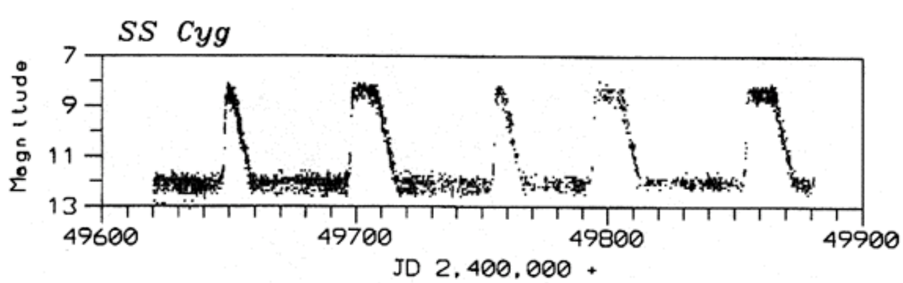
SS Cygni is one of the most famous variables in the sky. It is an eruptive variable of the U Geminorum type. Like most U Gem stars, SS Cyg is part of a spectroscopic binary system-a close system with a cool main sequence star orbiting a white dwarf. The cool star loses matter from its surface, which accumulates in an accretion disk around the white dwarf. For as yet not well understood reasons, the disk becomes unstable and the disk material spirals towards the white dwarf triggering a small nova-like eruption in this dwarf nova system. (Hence the name of dwarf novae given to U Gem variables.) Every few weeks, on average, SS Cyg brightens from magnitude 12 to magnitude 8. At minimum, it can be observed with a small telescope. At maximum, it can be observed with binoculars.

SS Cyg is a spectroscopic binary consisting of dwarf G and subdwarf B spectral class components. The orbital period is 6 hours and 38 minutes; however, no eclipses are observed so the plane of the orbit must be considerably inclined to the line of sight. In other words, from our perspective here on Earth, one star does not pass in front of or behind the other. Spectroscopically, the system alternates between the spectrum of the dwarf G (5520K) during minimum and the subdwarf B component during maximum. As the star rises to maximum, the spectrum changes progressively to that of the subdwarf B star (12,000K).

Visual observations of SS Cyg have become particularly important since it was discovered from satellite observations that SS Cyg is an extreme ultraviolet, and X-ray emitter. The satellite users depend on visual observers to tell them when the star is bright and active, and therefore worthy of further observation by satellite. Observations by amateur astronomers are necessary because the period of SS Cyg is not predictable. The rise to maximum is generally quite rapid, but by no means uniform. Some outbursts are quite short in duration. The light curve of other outbursts may be quite flat for several days at maximum. It then gradually slopes until a more rapid decline sets in. Occasionally there is a slight brightening before the actual maximum, and at other times there is a change from a steep slope to a more gradual one during the decline.

The minimum is the star's quiescent time. At times the light curve is quite flat and at other times quite irregular, with occasional rises in magnitude to at least magnitude 10.0 or brighter, preceding regular maximum.

SS Cygni has had over 700 outbursts since its discovery in 1896 and not one outburst has gone undetected. Statistical studies have shown that there are correlations between light curve characteristics such as the brightness and duration of outbursts and the interval between them. If you wish to study these correlations, you may through the HOA Website-request long term data of SS Cygni from the AAVSO International Database.



Activity 12.5: Folded Light Curves of Star X and Delta Cep

1. If you have completed Core Activity 6.5 in Chapter 6 and calculated the period for Star X, you may now use your own estimated period for Star X as the period *P*, and take the brightest single observation as a rough estimate of the epoch t_o, or time of maximum.

2. Using this period and epoch, and your data for Star X, follow the same procedure as in Core Activity 12.4. You will end up with a standard folded light curve of Star X.

3. Study the resulting diagram. Is your period accurate? Is there a lot of scatter? Is the epoch accurate? Is the maximum at (or near) phase 0?

4. Construct another standard folded light curve of Star X, but this time use the class average period as your period *P*. Are the folded light curves the same? Which period estimate do you think is more accurate?

5. If you have observed delta Cep, use your own observational data and estimate the period for delta Cep to construct a standard folded light curve. Was your period accurate?

Core Activity 12.6: VSTAR

Let's say that you suspect that your data are fluctuating with some particular period. You could test this period by using it to construct a phase diagram. If the scatter in the resulting phase diagram is much less than the scatter in the data, then you have evidence that your data are fluctuating with that particular period.

You could even use this strategy to find an unknown period: simply test a *very* large number of periods by constructing phase diagrams. For a Mira-type variable, you might test periods from as short as 100 days to as long as 1000 days, in 0.1-day steps. So you would construct one phase diagram to test the period 100 days, another phase diagram to test the period 100.1 days, another for 100.2 days, etc., all the way up to 1000 days. That's a lot of phase diagrams!

It takes too long to do this by hand, but this kind of work is ideally suited to a computer. This particular period search method is one of the most common in astronomy. It is called the *analysis of variance*, also known as *AOV*. The VSTAR program will search for periods in your data, using AOV. If you find a likely period, it will construct a phase diagram for you.

Run the VSTAR program, and again select the star V Cas. Load the data from JD 2447000 to 2449000. Now hit the <F4> key (AOV (period)). It will ask you for the "number of bins" and suggest the answer 20; this is a good choice in this case, so just hit <ENTER>. You will see the "period analysis" menu.

Select option <F2> (frequency range). When it asks you for the "low frequency to test," enter 0.001, when it asks for the "high frequency to test," enter 0.01, and when it asks for the "frequency resolution," enter a 0 (which tells VSTAR to pick the resolution itself). Finally, when it asks "AOK?," answer "Y" and watch what happens.

VSTAR will test a lot of periods (frequencies), and for each period it tests it computes a *power* level. The power level is a measure of the likelihood that the data are periodic for a particular period. Power levels higher than 10 mean that the data *might* be periodic (or might *not*). As it computes, VSTAR draws a graph for you, showing power as a function of frequency. This is the most basic graph in period analysis: it is called a *periodogram*.

Possible periods show up as large power values, and on the periodogram plot they look like spikes. So when you see a spike in the periodogram, it represents a *possible* period. VSTAR saves the period of the ten tallest spikes in its "top-ten" list so you can access them later. After the periodogram plot is finished, hit the <F4> key. Now VSTAR shows you the top-ten list, giving the period and power level. Can you tell by looking which list entry goes with which spike on the graph?

When you hit <F4>, VSTAR also asks which entries you want to delete. Enter "4-10," so VSTAR will delete entries 4 through 10, leaving only 1, 2, and 3. These are certainly the most likely possible periods. Then give no answer to the "delete" question, and VSTAR will return you to the period analysis menu. Now hit the <F5> key (model the data). VSTAR asks which frequency to include. Enter "1" (to use the #1 period), and VSTAR will construct and display a phase diagram, using that period. VSTAR will ask if you want to "save to a file" (say "N" for no).

CAUTIONARY NOTE: When VSTAR shows you a phase diagram, it does not show two complete cycles, only one. Also, it does not put the maximum at phase zero; it chooses an epoch at random. So be prepared: if you see two complete cycles, it is not because it is a standard folded light curve! It is because your period is too long—you have gotten two cycles per period. Hit <F5> again, and this time choose period #2. You will see two complete cycles, because this is the wrong period! Period #2 is the twice the true period. Model the data again, using period #3, and you will see three complete cycles, because this is also the wrong period; it is three times too long.

When you fold the data using the correct period, you get a nice folded light curve of one cycle. When you fold the data using twice (or three times, four times, or any multiple of) the correct period, you also get a nice folded light curve, but of more than one cycle. So when VSTAR shows many possible periods, it is up to you to look at them, and decide which one is real.

If the true period is P, then its multiples are 2P, 3P, 4P, etc. Even though they give a high power level, they are not the true period, they are *aliases*. Since the frequency is f=1/P, the alias frequencies are 1/(2P), 1/(3P), 1/(4P), etc. So when the data are periodic with frequency f, you will get a spike at frequency f, and at frequencies f/2, f/3, f/4, etc. These alias frequencies are called *subharmonics*; it is a property of AOV that it gives high power levels not only for the true period (frequency), but also for its subharmonics. It is up to the analyst (you!) to decide which is real and which is an alias.

When you have decided which period is real, use that period to model the data. Now when you are asked whether you want to save to a file, say "Y" for yes. Then pick a file name for the saved information. VSTAR will create a file containing both phase and magnitude (just what is needed to plot the standard folded light curve). It will give you two complete cycles, and it will also estimate the maximum, choosing an epoch so that maximum is at phase zero: the standard folded light curve. See the VSTAR manual for the layout of this file. Plot the standard folded light curve for V Cas from JD 2,447,000 to 2,449,000. You will need to use a graphing program for this (there are too many data points to do it by hand!).

Now repeat the entire procedure, but instead of using the data from JD 2,447,000 to2,449,000, use the data from JD 2,440,000 to 2,442,000. Now you have *two* folded light curves, covering two different time periods. They show the *average* shape of the light curve during those time intervals. Are they the same? Is the average maximum brightness the same? Minimum? Is the *shape* of the average light curve the same?

Finally, a most interesting question: why does VSTAR show a spike at periods which are multiples of the true period (in other words, why does AOV respond to subharmonics)?

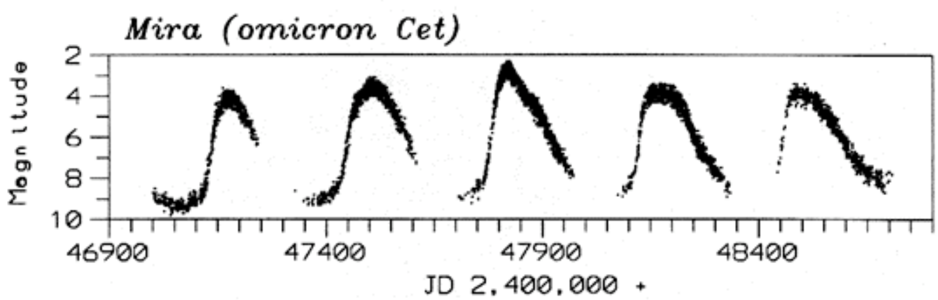
SPACE TALK

Mira stars are long-period, pulsating red giants of approximately the Sun's mass that have entered the final evolutionary stages of their existence and will eventually become white dwarfs. Miras have nearly exhausted the supply of hydrogen in their cores. Their cores are very dense and are composed mostly of oxygen and carbon (products of helium fusion). Just outside the core, a shell of hydrogen is still being converted to helium, and this layer of helium builds up on the surface of the core. Every few thousand years enough helium builds up and then ignites, creating even more carbon and oxygen. When the helium-burning begins, the shell rapidly expands and the hydrogen-burning turns off. This is known as **helium flash**. When most of the helium is consumed, the flash ends, the shell shrinks, and hydrogen-burning resumes. This process can happen over and over again for 50,000 to 100,000 years before the outer layers are thrown off to form a planetary nebula. The core remains as a white dwarf, its nuclear fires finally out.

1996 marked the 400th anniversary of the discovery of the first Mira-type variable star. It is located in the constellation Cetus the Whale, and is known as Omicron (o) Ceti, or Mira, and was the very first known periodic variable star. David Fabricius, a clergyman and amateur astronomer in Friesland, Germany, noticed the "new" star in Cetus on August 13, 1596. Fabricius checked every star catalogue, atlas, and globe that existed and saw that the star was not listed. He observed Mira again at the beginning of September and watched it fade below naked-eye visibility during the middle of October. Fabricius assumed that his star was a nova similar to Tycho's nova discovered in Cassiopeia (Supernova of 1572). As a result, Fabricius did not check the star after it dimmed, because novae do not brighten more than once. He did not notice the star again until 1609. Fabricius might have studied his star more systematically with the recent development of the telescope, but unfortunately he met an untimely end when he was murdered by a member of his own parish in 1617. (He had recently announced from the pulpit that he knew which member of his parish had stolen one of his geese!)

Mira was listed in Johann Bayer's 1603 star atlas *Uranometria* as an ordinary 4th-magnitude star labeled Omicron. Another German astronomer, John Holwarda, also from Friesland, discovered in the winter of 1638–39 that Mira had brightened, and realized that it would probably repeat the increase in magnitude. Every maximum since 1638 has been observed except for those times when Mira's apparent position in the sky appeared too close to the Sun to be seen, which occurs from April to the end of June each year. In 1667, Ismael Boulliau announced that Mira's variations were periodic and that the star brightened every 333 days. The period is 331.96 days, as published in the 4th edition (1985) of the ***General Catalogue of Variable Stars*** (GCVS). Johannes Hevelius, who named the star Mira ("the wonderful"), began observing it regularly in 1648, and in 1662 published a pamphlet about the star entitled "Historiola Mirae Stellae" ("Brief History of the Wonderful Star"). In 1926, Sir Arthur Eddington gave the correct explanation for the behavior of Mira-like variables—that these stars pulsate the same way Cepheid variables do, but with longer periods because of their more distended physical size and lower surface gravity.

Mira typically ranges in brightness from magnitude 9.3 to 3.4. In some cycles Mira brightens to a brilliant 2nd magnitude, and in other cycles barely reaches 5th magnitude. The brightest maximum on record occurred in November of 1779, when William Herschel observed Mira to be almost as bright as Aldebaran (magnitude 0.9). Maxima observed since 1906 by members of the AAVSO have ranged from 2.4 to 4.9, and minima have ranged from 8.4 to 9.7. The period also displays irregularities, with maxima arriving three weeks earlier or later than predicted. Unlike most Mira-type variables, omicron Ceti is a double star system. It has a 10th-magnitude companion, a hot dwarf called VZ Ceti. This companion was seen for the first time in 1923, although it had been detected by spectroscopic methods 5 years earlier. The irregularities in Mira's variations are obvious in the AAVSO light curve shown below, based on more than 17,000 observations by amateur astronomers over the past 25 years.



A star pulsates because it is not in **hydrostatic equilibrium**: the force of gravity acting on the outer mass of the star is not quite balanced by the interior radiation pressure pushing outwards. If a star expands as a result of increased gas pressure, the material density and pressure decrease until the point that hydrostatic equilibrium is reached and then overshot, owing to the **momentum** of the expansion. Then gravity dominates, and the star begins to contract. The momentum of the infalling material carries the contraction beyond the equilibrium point. The pressure is again too high, and the cycle starts over again. The system acts as an **oscillator**. However, with loose atmospheric layers of gases, the oscillations get out of sync, or phase, with one another and set the stage for chaotic motions. Energy is dissipated during such pulsation (analogous to losses caused by friction forces), and eventually this loss of energy should result in a damping or lessening of the pulsations. The prevalence and regularity of pulsating stars imply that the dissipated energy is replenished in some way. This kind of statistical conclusion requires very long runs of data, such as those collected by the AAVSO.

Mira stars are not entirely predictable, and individual cycle lengths can be several weeks shorter or longer than the mean. Miras also undergo small, longer-lasting changes in their periods which are revealed by sophisticated statistical techniques. Subtle departures from regular behavior are characteristic of these stars. However, a handful of Miras go way beyond subtle changes, instead exhibiting extreme period changes that indicate radical physical changes within the interior of the star. One such star is R Hydrae, the third Mira-type variable discovered, located ~325 light-years away. (The second Mira-type variable discovered was chi Cygni in 1686.) R Hydrae missed discovery twice, once by Johannes Hevelius who recorded it in his star catalog simply as a 6th-magnitude star, and once by Geminiano Montanari, the Italian astronomer who worked at Bologna and discovered the variability of Algol in 1669. Montanari noticed R Hydrae at naked-eye brightness in April 1670, noted that it was not listed in Bayer's *Uranometria* star catalog, and added it to his copy by hand. Montanari's copy of *Uranometria* ended up in the possession of Giacomo Maraldi, who worked with his uncle, Giovanni Cassini, at the Paris Observatory. (Cassini discovered the division in the rings of Saturn which now bears his name.) Maraldi saw the handwritten notation in the star catalogue and began searching for the star in 1702, finally discovering it two years later at 4th magnitude.

The most remarkable aspect of R Hydrae is its slow but dramatic shortening of period, from 495 days during early observations to only 389 days during the last 60 years. For the first century of observation, R Hydrae's period decreased at a nearly constant rate, from 485 days/cycle around the year 1800 to 400 days/cycle around 1910. From 1923 to 1935, the period slowed to 415 days, then suddenly increased again. Since 1937, the period has remained constant at 389 days. The century of steady decrease in R Hydrae's period is consistent with theoretical calculations of what happens to a pulsating red giant after helium flash. R Hydrae is still recovering from such an event.

Amateur variable star observers usually do not get to actually observe the dramatic changes that evolving red giants undergo. One exception is that of T Ursae Minoris, a red variable in the bowl of the Little Dipper. After decades of constant periodicity, the pulsations of T Ursae Minoris started to increase drastically, probably due to the earliest stages of helium flash. Before 1980, the period ranged from 310 to 315 days, but since 1980, it has decreased steadily to 274 days. If the theoretical models of stellar evolution are correct, T Ursae Minoris should continue shortening its period until it reaches a minimum period of 200 days (around the year 2030), after which its period will once again lengthen.

POSTER TALK: "Theoretical Glue": Understanding the Observed Properties of Miras with the Help of Theoretical Models

by Dr. Lee Anne Willson

Lee Anne Willson, Professor of Astronomy at Iowa State University, is an internationally-recognized expert on Mira variable stars. The following is an adaptation of a paper she presented at a special scientific conference on Mira stars sponsored by the AAVSO in 1996. The full text, including additional references and bibliography, can be found in *The Journal of the AAVSO*, Volume 25, No. 2, pages 99–114.

1. Introduction

Each observational study of Mira variables has as its goal to determine some quantities describing these stars. However, observations alone do not give us an understanding of what we are seeing. Theoretical models are needed both to connect what is observed to the qualities of the star, and to link the various measurements into one coherent picture of its nature. It is in this sense that a good model is a kind of "glue" holding the picture together.

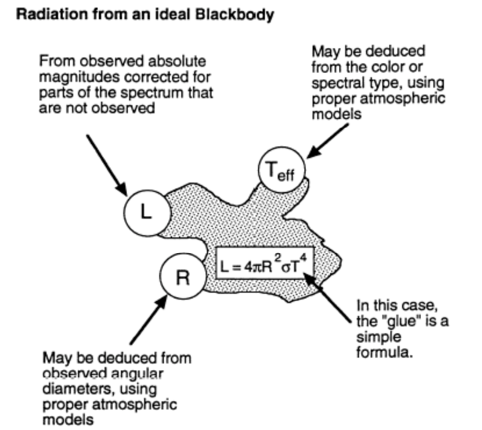


Figure 1. The definition of effective temperature (T_{eff}) illustrating the concept of theory as "glue."

Figure 1 illustrates the concept of "theoretical glue" by showing how the luminosity L, the radius R, and the effective temperature T_{eff} are related by the theoretical (and lab-tested) model of a blackbody "perfect radiator." Such a perfectly radiating surface emits power per unit surface area that increases as the fourth power of T (in Kelvins), so a doubling of the temperature gives a 16-fold increase in the total amount of radiation (light, infrared, ultraviolet, X-rays and so on) coming from each patch of the surface. If stars were, in fact, ideal blackbodies, then their radiation would be completely known and the problem of relating L, R, and the temperature of the surface would be trivial. However, real stars are gas spheres; we can only see into the atmosphere on the average down to the apparent surface, the photosphere. We define the "effective" temperature T_{eff} as the temperature of a blackbody of the same size as the star that radiates the same total power, L. This gives the equation $L = 4\pi r^2\sigma T_{eff}^4$ with $\sigma = 5.670 \times 10^{-8}$ watts per square meter per second per $(\text{Kelvin})^4$. Moreover, the stellar atmosphere is not all at one single temperature, and we see to different depths at different wavelengths; as a result, the spectrum we see has high and low spots compared with an ideal blackbody spectrum. Typically, the effective temperature is close to the gas temperature at the photosphere, but is not identical to it. We have to use a theoretical model atmosphere to relate effective temperature to the spectrum we see and to the temperature at the photosphere.

For Miras and other pulsating variables, even more than for most stars, the process of translating "what is actually observed" into "what the star is really like" can lead the incautious investigator astray. For example: To get the luminosity—the total power output, energy per second—we observe the visible part of the spectrum and, if we are lucky, also the near-infrared and perhaps the ultraviolet, in detail or using broad-band photometry. We then use a model of some sort to estimate how much light we are missing in the parts of the spectrum that we can't see, and finally we correct for distance. How good our final result is will depend on how good the model is that we use to fill in the "missing bits," as well as on how much of the spectrum we could actually observe and how accurately we know the distance. The expected (and sometimes observed) spectra of Miras are very far from the simplest case—a blackbody spectrum—so detailed models are essential. Worse, the molecules that produce some of the deepest spectral features in Miras are also found in Earth's atmosphere, and so we are selectively less likely to observe the depressed parts of the spectrum.

2. Classical model atmospheres

The calculation of a classical stellar atmosphere begins with a choice of stellar parameters—for example, composition, effective temperature, and surface gravity. The propagation of energy from the interior of the star through the atmosphere and into space is then calculated, taking into account the effects of the different atoms, ions, and perhaps molecules that can absorb and emit light. The result of a classical atmosphere calculation may include any or all of a predicted spectrum, a model for the pattern of brightness that you would see if you could get close to the star, and predicted values for the photometric colors. Such models play a key role in the determination of the luminosities of stars, and also in the derivation of their radii.

To get an estimate for the radius or diameter of a star, we may use an interferometer or a lunar occultation to get a pattern of fringes that may be interpreted by using a model for the brightness pattern on the star. Or, we may try to relate the appearance of the spectrum to the effective temperature T_{eff} using a detailed model atmosphere, and then deduce R from L and T_{eff}. If these methods give the same answer, it increases our faith that the model is close to describing what happens on the star.

To find the composition of the atmosphere, the line spectrum is analyzed using a stellar model atmosphere. Thirty years ago, most such calculations were made using some reference model atmospheres and looking for differences using methods such as the "curve of growth." Today, it is possible to carry out most analyses by making model atmospheres with a range of compositions and selecting the composition pattern that produces a spectrum that best matches the observations.

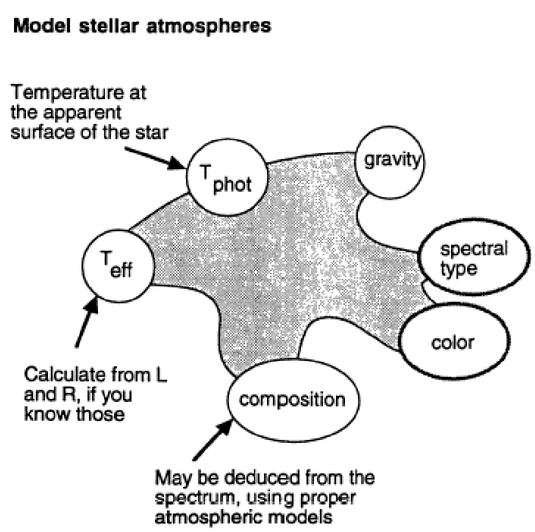


Figure 2. Classical model atmospheres as "glue" for the colors and spectra.

Figure 2 illustrates how a classical stellar model atmosphere glues together observable and non-observable quantities for stars. In a classical model atmosphere there is no net outflow of matter—no stellar wind—and there are no systematic motions, such as one might get from pulsation. Obviously, this is not going to work perfectly for modeling Miras! Also, in classical atmospheres, each part of the atmosphere is in radiative equilibrium—meaning that the radiant energy flowing into a sample volume of the gas per second exactly equals the radiant energy flowing out of the same sample volume per second. In more modern model atmospheres, other forms of energy are also considered, and energy is allowed to shift from one form to another—for example, from May be deduced from the spectrum, using proper sound waves to radiation. There are still relatively few models, however, that include dynamical effects and outflows.

One of the important ingredients in a stellar atmosphere model—whether classical or modern—is the surface gravity $g = GM/R^2$, where G is the gravitational constant, and M is the mass of a pulsating star. This combination of M and R turns out to be important for the spectrum because higher gravity compresses the atmosphere more. One can deduce a gravity by computing synthetic spectra for models with a range of surface gravities, and then picking the model whose spectrum best matches the star, as long as the model does produce a good match. This works reasonably well for most non-variable stars, but does not do a good job with the variable ones. Other methods are needed for these, at least for now.

3. Glue from pulsation and evolution studies

In principle it should be easier to derive a value for the surface gravity for a pulsating star, because the material in the atmosphere is moving in response to gravity during much of the cycle. Thus, one might observe the change in velocity over some interval of time and estimate $\Delta v/\Delta t = g$. Because the excursion in radius is large (so g is not the same at all parts of the path) and because pressure forces are also important, the above method typically underestimates g by a factor of five or so. Instead, a dynamical atmosphere model needs to be used to interpret the result. Also, you need a good radiative transfer model to be able to interpret the observed Doppler shift in terms of the motions of parts of the atmosphere, because only part of what you see is moving towards or away from you. To get a meaningful Δv from the Doppler shift requires a fairly detailed model for the atmosphere, and this correction is still rather rough for most variable stars.

There is another way to get a combination of M and R for pulsating stars. A given star is usually able to pulsate only in one or a small number of modes, each with a distinct period associated with it. Detailed models for the interior of a pulsating star can be analyzed to reveal the period(s) that are possible, and these can be related through formulae such as (for example), $P = aR^bM^c$, as is illustrated in Figure 3. (Usually b is between 1.5 and 2, and c is between –0.5 and –1.)

There are assumptions that go into this kind of modeling that need to be tested more thoroughly than has been possible so far: for example, the period of pulsation of a star pulsating at full amplitude may not be the same as the period derived looking at very small pulsations in a model for a static star.

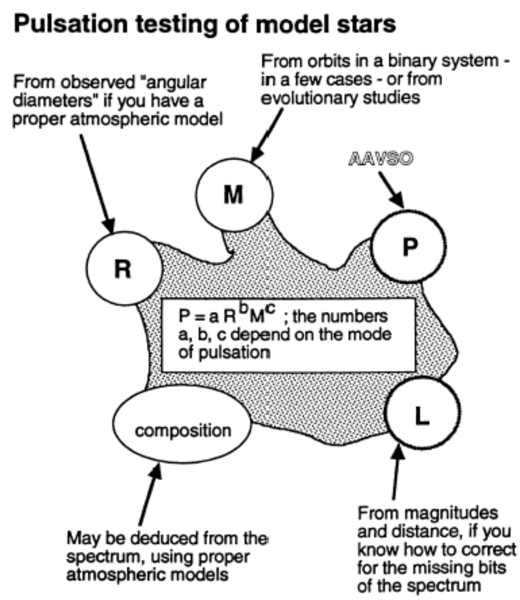


Figure 3. Pulsation periods from model stellar interiors connect evolutionary models to stellar parameters.

A PMR relation is often used to estimate the mass of a pulsating star, M, given its radius, R (which may have been derived from L and T_{eff} or from angular diameter measurements), assuming that one knows the mode of pulsation. It can otherwise be used to determine the pulsation mode(s), if one is confident of M and R from other measures. For most classes of stars this is relatively easy to do, and the results are consistent with whatever else one knows about the stars. However, for Miras the radii and masses are still sufficiently uncertain that this method does not even yield an incontrovertible result about the pulsation mode, much less useful estimates for their masses.

4. Models for stellar evolution

The most important "theoretical glue" in stellar astronomy is the study of how stars evolve. Starting with some composition (assumed to apply throughout the star) and a mass, M, a model is found that obeys relevant physical equations and is in hydrostatic equilibrium. For all but the lowest-mass stars the model will include energy generation by nuclear reactions in the core. These reactions modify the composition at the center, so some time later the star's structure will be a little different and its L and R may also be a little different. By building a sequence of static models that are related by the condition that the change of composition comes from the nuclear reactions, one can model the evolution of the star.

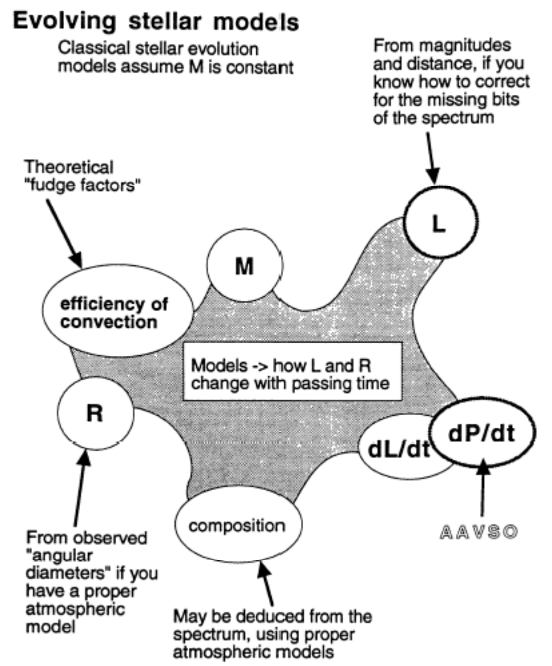


Figure 4. Evolutionary models link stars in different evolutionary states as well as relating stellar properties and (occasionally) rates of change of those properties.

In most evolutionary calculations the mass M is not allowed to change with time, although there are times in the life of a star when the mass decreases as the result of mass loss from the surface. The change in mass that comes from the conversion of mass to energy in the nuclear reactions is almost always small enough to ignore. One time when the mass loss is particularly important is the Mira stage, and this fact is a major reason why Mira models are not yet in a settled state.

Since much of stellar evolution proceeds at constant mass, and since L and T_{eff} are the easiest quantities to estimate directly from observations, we traditionally plot tracks for constant mass stars in a diagram of L versus T_{eff}, one variant of the Hertzsprung-Russell diagram. One may then think of evolutionary tracks as linking L, M, T_{eff} or R, initial composition, and age for the star (Figure 4).

In addition to the problem of how to include mass loss in a realistic way, evolutionary models also suffer from our lack of detailed understanding of convection in stars; of rotation inside stars; of the effects of magnetic fields in stars; and so on. Most astronomers assume that these effects will turn out to be small, but others would not be surprised to learn that some of them affect the "big picture."

5. Dynamical models for the atmospheres of pulsating stars

If we know how a star is pulsating, then we can model the response of the outer parts of the star (the atmosphere) to this pulsation. Figure 5 shows the connections that can be made this way. In practice, L, M, and T_{eff} or R are assumed; also a pulsation period P is assigned (using a PMR relation) and the bottom of the atmosphere is made to move in and out with period P.

Dynamical models require some understanding of the interaction between the gas and the radiation. The pulsation generates waves that compress the gas, heating it. It then cools by radiating away energy, and also by expanding. Depending on the density of the gas, the conversion of internal energy into radiation may be fast (compared with the pulsation time) or slow. Where it is fast, the material cools to roughly the equilibrium temperature that it would have in a static model, and then as it expands it may be refrigerated below the temperature it would have in the static case.* Where the density is lower, the cooling is less efficient; there, the temperature may never fall as low as the equilibrium temperature. Some dynamical model results are very sensitive to the treatment of these processes; mass loss is one example. Since the details of how the gas emits or absorbs radiation at low density involve many non-equilibrium chemical processes, this is definitely one of the frontier areas in dynamical atmosphere modeling.

*Since the density is highest just after the gas is compressed, there is a region in the atmosphere where it can lose energy to radiation immediately after compression but has a harder time regaining energy near the end of its expansion. We can describe this approximately by saying that the shock is nearly isothermal-it returns to the radiative equilibrium temperature quickly-but the expansion between shocks becomes nearly adiabatic-without gain or loss of energy.

A detailed treatment of the interaction between gas and radiation—the radiative transfer problem—is also required in order to synthesize the spectrum and colors that would be observed, as well as the light curve. So far, there is no model for Miras or other pulsating stars that includes enough detail to do this effectively. However, dynamical models that are now available provide important insight into the motions of the atmospheres and the mass loss rates that result. For example, Bowen's models (Bowen 1988, 1990) have atmospheric motions and conditions that match what we deduce from observations—shocks with velocity amplitudes of 20 to 30 km/s, warm regions in some, dust formation in others, and so on. In fact, the success of dynamical models in matching velocity variations observed in the infrared CO lines is the best evidence we have about the mode of pulsation of these stars—fundamental mode models match well, but overtone models (with larger radius at a given P) are quite far from matching, as was first noted nearly 20 years ago (Hill and Willson 1979).

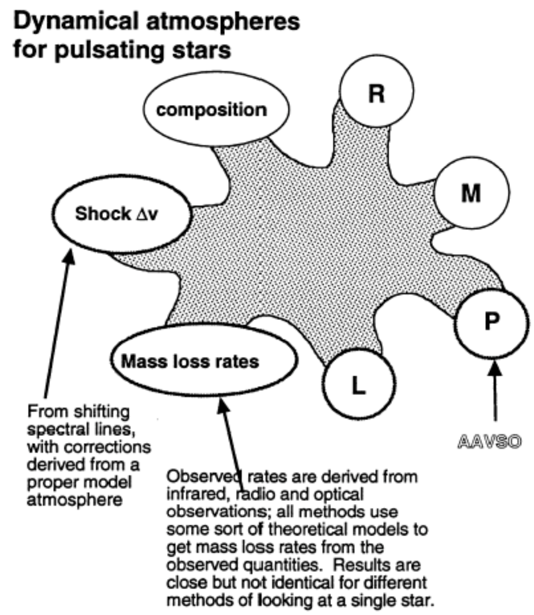


Figure 5. Dynamical model atmospheres are required for pulsating stars, such as Mira variables.

6. Some results of recent "glue" production

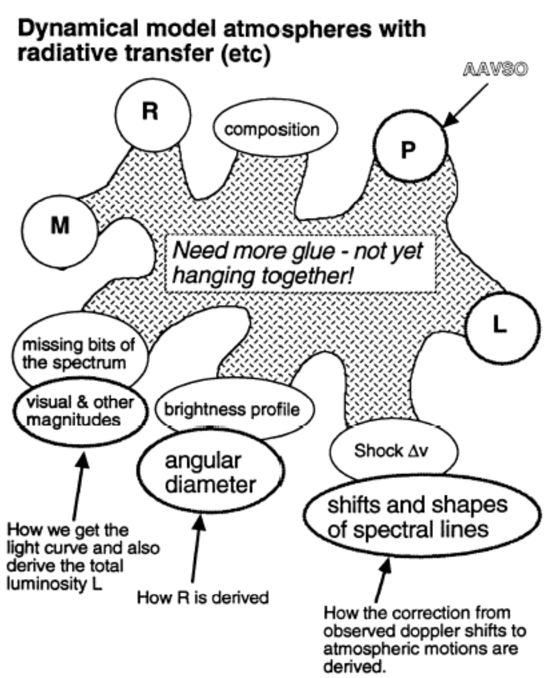


Figure 6. Ideally, radiative transfer, non-equilibrium chemistry, and detailed hydrodynamics are included in the models. In practice, no one model yet includes all the details that are needed to reproduce all the observations.

Bowen's latest grid of dynamical atmosphere models is a collection of models that are constrained by stellar evolution calculations: once L, M, and initial composition are chosen the evolutionary calculations are used to derive R, and then a theoretical PMR relation gives P. This single step of requiring the stars to fall on a single set of evolutionary tracks turns out to make quite a big difference in the way that the mass loss is understood to develop. The choice of which tracks to use is not so important as is the fact that using tracks forces certain relationships between models: For a given mass, as a star increases in luminosity it also increases in radius with (slightly) decreasing T_{eff}. Two stars with the same L and different masses will be separated in T_{eff} or R. Two stars of the same L and M but different composition will also be separated in T_{eff} or R: lower metallicity stars are hotter and smaller at a given L.

Bowen's models, constrained in this way, predict mass loss rates that are very sensitive to stellar L, R, and M. Since all of these parameters vary in a predictable way along a given evolutionary track, we can display the results as mass loss rate M versus L for a given mass, where for a given metallicity L and M together also determine R, T_{eff}, and P as well. Figure 6 shows the result of these calculations for stars whose composition matches that of the Sun.

7. Conclusion: where we need some new glue

Many pieces of the puzzle of Miras and other pulsating variable stars are well-glued together by these theoretical calculations, but some very basic properties remain "unglued." The outstanding problem in the case of the Miras remains the determination of their absolute sizes; here, uncertainties of factors of two or more are still a problem. Clearly we need more and better "glue"—new models that incorporate more of the physics that we already know is important in producing what is observed.

References

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Bowen, G. H. 1990, in *Numerical Modeling of Nonlinear Stellar Pulsations: Problems and Prospects*, NATO Advanced Research Workshop, J. R. Buchler, ed. Dordrecht, The Netherlands: Kluwer Academic Publishers, 155.

Hill, S. J., and Willson, L. A. 1979, *Astrophys*. J., 229, 1029

Chapter 12: Variable Stars and Phase Diagrams

Summary

Phase is the fractional part of a cycle of variation, and a graph of magnitude versus phase is called a phase diagram. A phase diagram shows the average behavior of a star during its cycle and helps to more accurately determine the measured period. This chapter presents both mathematical and computer statistical analysis techniques to determine periodicity.

Terminology

folded light curve	hydrostatic equilibrium	mometum
General Catalogue of Variable Stars	Mira	oscillator
helium flash	modular arithmetic	phase

SUGGESTIONS FOR THE POSTER PAGES, INVESTIGATIONS, AND ACTIVITIES

Investigation 12.1: Periodic Cycles

The concept of phase is extremely important, and phase diagrams are powerful tools in deciphering variable star behaviors. Let the students explore this activity until they have an appreciation for the phenemonon of phase (i.e., that if all cycles are the same, it is not important which cycle is represented, only which part of the cycle). The students have a paper copy representing a portion of the light curve of V Cas. After the students have studied their paper model, make several overhead transparency copies for the class from the template following student page 208. Have them cut out the transparency models and lay them on top of each other. Students can then experiment with having a different starting point in the cycle. Have them try several ways of superimposing them, laying them end-to-end, and taping them together. Practicing with different beginnings to the cycle will help them appreciate what is meant by phase. No matter what they do, the results will always be the same—no matter when the first observation is taken in a star's cycle, no matter what point is chosen for the reference point on their phase diagram, the diagram will represent the behavior of the star. Even though there are minor differences, they can cut their model up into single cycles and lay them all on top of one another and see that one cycle is representative of all the behavior exhibited by the light curve of V Cas provided.

Core Activity 12.2: Folded Light Curve of the Variable Star SV Vul

This activity leads the students through the steps of constructing a folded light curve. Depending upon your group, this can be an independent classroom activity, or presented as a demonstration to the entire class. If necessary, review graphing techniques. The students are going to complete this same activity two more times. Each successive activity will involve a greater degree of complexity. With this first graph, the students will plot two cycles on top of each other, as in Figure 12.2. This will give them the basic idea of how a folded light curve is produced by plotting magnitude versus phase. A completed graph of this activity is provided on the opposite page.

Core Activity 12.3: Another Folded Light Curve of SV Vul

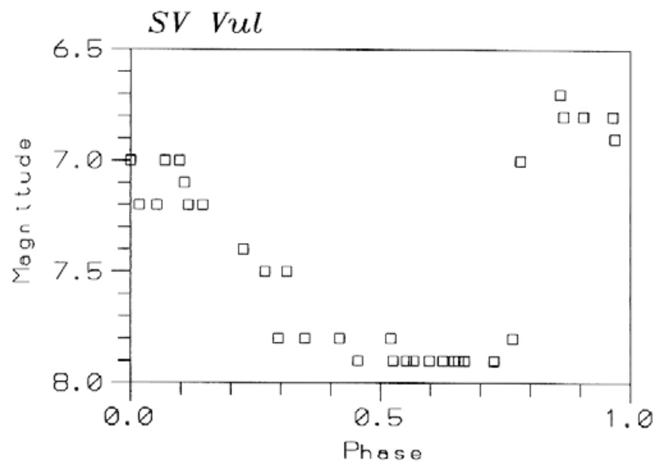
This time the students will plot each data point twice for two continuous phases so they have a graph of two complete cycles of behavior. This way neither the activity at maximum or minimum is cut off so the continuous cycle of activity can be easily seen. Since two consecutive cycles are represented, the 0 reference point is centered in the diagram and the phase runs from –1 to +1. A completed graph of this activity is provided on the opposite page.

Core Activity 12.4: Yet Another Folded Light Curve of SV Vul

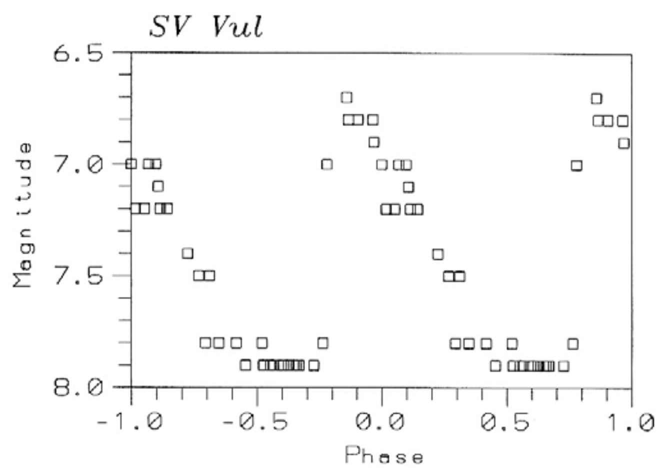
For the final graph, the students will plot the data the same way as in the previous graph with one important difference. Now instead of having the first JD as the reference point or 0 point, the more standardized method of using a JD when a variable star is at maximum is used. The phase still runs from -1 to +1; however, now the calculation of the JD from the JD at time of maximum is different, to take into account the negative numbers which will result. From now on, students should always calculate folded light curves using a time of maximum (except when analyzing eclipsing binaries, in which case a time of minimum is used) for the starting JD and plot two consecutive phases from –1to +1 on their graphs. A completed graph of this activity is provided on the next page.

Completed Folded Light Curves for:

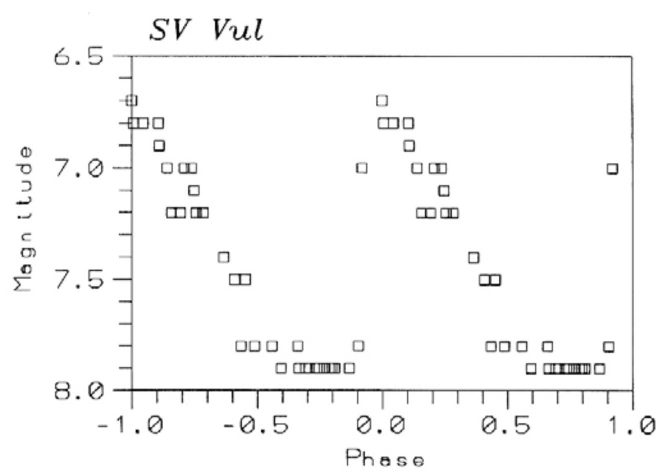
Core Activity 12.2



Core Activity 12.3



Core Activity 12.4



Poster Page: SS Cygni

Someone had to be the first person to recognize SS Cygni as a variable star. All variable stars, novae, supernovae, known comets, and asteroids were "discovered" by someone. The more recent ones are well documented; however, sometimes more ancient documents have gotten lost or misplaced over time. The history of the discoveries of some stars, such as: SS Cyg, Mira, and delta Cep, have been discussed within this manual. Have your students choose a star and try to find who first discovered its particular properties, or, in some cases, did not know that they had seen something new. Some astronomers just happened to be looking at the right part of the sky when something was about to happen, as with SN 1987A. Others looked at photographic plates for years before making a discovery, such as Clyde Tombaugh's discovery of Pluto.

Core Activity 12.5: Folded Light Curve of Star X and Delta Cep

You may have the students select what information to use for the phase diagram, or you could have different groups use different information in order to compare the results. They have their individual data, the classroom averages, and the results of Pogson's method of bisected chords, all of which probably gave a different period, so different groups can use the different periods in constructing the phase diagram. This would lead to additional classroom discussion about which results are more acceptable or reliable than others.

If the class has its own observational data, a folded light curve for delta Cep can now be constructed. Again, they can use their own measured period or the class average, or the results from Pogson's method. Perhaps they can compare results with other classrooms in other locations, or average all the data together to see the differences from or similarities to small data sets. If you have not yet given them the actual period of delta Cep, they can now ascertain on their own if their period determination was reasonable.

Core Activity 12.6: VSTAR

VSTAR

Now that students have gained an understanding of why plotting magnitude versus phase to get a folded light curve is a good method of presenting variable star data for further analysis, they are ready to let VSTAR do the work for them. This activity takes the students through the process of learning how the program determines the best period for a variable star.

Poster Talk: Theoretical Glue

This discussion incorporates many of the topics that have been introduced throughout this manual. It is an excellent example of how scientists rely on each other to construct knowledge. Scientists keep themselves current in research results within their fields of interest by accessing publications and technical journals. Any information they then use in their studies from other sources is listed when they in turn publish an article.

Models were discussed in the beginning chapters. A model of the surface of Earth, for example, is a simplistic model. We can easily understand the relationship of oceans, seas, and continents by looking at a globe. Models of stellar evolution are complex and dynamic. Scientists start with a simple model which poorly represents the actual star, and then build more and more complex models in an attempt to construct a model which is accurate enough to give further understanding of the processes involved

Chapter 13: Variable Stars and *O–C* Diagrams

Artist, Miranda Read

Introduction

In the previous chapter we stated that a *perfectly periodic* system repeats exactly the same behavior, over and over again. Every cycle is precisely like every other cycle. Some variable stars actually behave this way: Cepheid variables, for example, may repeat precisely the same brightness variations for thousands of cycles. Eclipsing binaries also sometimes repeat thousands of cycles, with exactly the same period every time.

Other variables are not quite so reliable. While they do go through an almost never-ending series of ups and downs, each cycle is a little different from every other cycle; the period will be slightly longer or shorter, and the maximum and minimum magnitudes will be slightly brighter or fainter. You probably noticed in the last chapter that the light curve of the Mira-type variable V Cas showed slight differences from cycle to cycle. It keeps brightening and dimming, so it definitely appears to be periodic, but it is not *perfectly periodic*.

In fact, all Mira-type variables behave this way. They are periodic, because they keep repeating cycles over and over again. But they are not perfectly periodic, because every cycle is a little different. For Mira-type variables, the differences from cycle to cycle are small. The period, for instance, will be a little different for each cycle, but is usually within 10% of its average value. The amplitude of each cycle (the difference between minimum and maximum brightness) will usually be within 20% of its average value. Each cycle in the light curve looks a bit different, but they all have many similarities as well, and they are usually close to the “average shape” of the light curve.

Another class of variables, known as the *semiregular variables*, show even greater differences from cycle to cycle. Not only are their periods not perfectly periodic, but these stars also sometimes “switch” from one period to another (a process known as *mode switching*). Their amplitudes change dramatically: they may suddenly increase their variability, or they may stop varying altogether (but when they do, they usually start up again soon after).

It is easy to see the differences from cycle to cycle in the light curves of Mira- and semiregular-type variables. The light curves of Cepheids show what appear to be identical cycles. But if we watch Cepheids long enough—for tens of thousands of cycles—we can detect very slight changes in their cycles as well. They too can show changes in the cycle shape, the amplitude, and the period. The differences are still there: even the Cepheids are not perfectly periodic.

Pulsating Stars

When the first Mira-type variables were discovered, it was a mystery why they were varying at all. After all, most stars, like our own Sun, are quite stable, not variable (even the Sun varies a *little* bit, but surprisingly little). In the early part of this century, the famous English astronomer Arthur Eddington studied the problem carefully. Most known ways that stars can vary could be eliminated from consideration. For example, Mira-type variables were not exploding like supernovae: their fluctuations are too regular for that. And they were not eclipsing like the eclipsing binaries: their fluctuations are not nearly regular enough for that.

Eddington went back to the basics. Stars glow like the filament of a light bulb for the same reason—because they are hot. The light output of a star depends mainly on two things: its surface temperature (how bright the light bulbs are) and its size (how many light bulbs are burning). The apparent visual magnitude of Mira itself is 100 times brighter at maximum than at minimum. To be so much brighter, it would either have to be hotter, or bigger, or both.

By studying the spectra of stars, we can get a good estimate of their temperatures. The spectrum of Mira throughout its cycle does change, and in fact Mira will show temperature changes while it fluctuates, but these temperature changes are just too small to explain the tremendous increase and decrease in brightness. That leaves only one possibility, said Eddington: Mira changes its brightness by a large amount every cycle because Mira changes its size by a large amount every cycle. Mira (and all Mira-type variables) fluctuate because they are expanding and contracting, growing and shrinking. The star is literally “vibrating.” Variables that do this are known as pulsating variables.

We now know that there are many types of pulsating variables. Cepheids, for example, are very regular pulsating variables, usually with periods of a few days or more. Mira-type variables also pulsate, but their periods are almost always more than 100 days, and their pulsations are much more irregular from cycle to cycle than those of Cepheid variables. Semiregular variables pulsate with periods from as little as 30 days to over 1,000 days, and their pulsations are even more irregular than those of Mira-type variables.

Period

Eddington’s “back-to-basics” approach was appropriate. After all, the stars are so far away that we have to stretch ourselves just to uncover their basic physical properties. The most important physical parameters of a star are its size (the radius) R, its surface temperature T, and its mass M.

Unfortunately, we cannot measure these basic quantities directly. The easiest to estimate is the temperature. The spectrum of the star acts almost like a thermometer to give us a good estimate of the temperature, and other clues enable us to refine this estimate. The radius can be quite difficult to determine, because the stars are so far away that we cannot really see their images directly (except in a few special cases). Still, if we know the star's distance from earth, its brightness, and its temperature, we can get a reasonable size estimate. Of all the "basic parameters," the most difficult to estimate is the mass: too often we simply have no clues, and our best mass estimate is likely to be very unreliable.

There are exceptions. Binary stars orbit each other, and their orbits are determined by the laws of gravity. The strength of gravity depends on mass, so if we know all the details of the orbital motion of a binary star, we can get a very good mass estimate. That is one of the reasons eclipsing binary stars are so important: the details of their orbital cycles enable us to determine stellar masses. Unfortunately, this can be applied only to a few stars.

Another exception is pulsating stars. The period of a pulsating star depends mainly on its basic physical parameters of size, temperature, and mass. So if we know the period, we have one more clue to help us estimate mass. In fact, the period of a pulsating star can give us clues about its mass, the strength of its gravity, and sometimes even the reactions taking place in the star's interior.

According to our theories of stellar structure, if a star is pulsating, its period in most cases will be stable. The period may change from cycle to cycle (as with Mira-type variables), but the *average* period over many cycles will remain the same. For the average period to change, we would have to change the star's mass, size, or temperature (none of which is very likely), *or* we would have to change the internal workings of the star. Such changes do occur, but they usually happen only at important stages in the star's life cycle. So when a pulsating star shows a change in its average period, it usually means that the star is undergoing an evolutionary change in its behavior, moving from one stage in its life cycle to the next.

We see that the period of a variable star is one of the most revealing aspects of its variations. It is something that we can obtain through careful observation. The average period gives us vital clues about a star's basic properties, including mass and gravity. Any period *changes* are a warning that the star may be entering an important new stage of its development. And this is true not just for pulsating variables: for any periodic variable star, the period is one of the most important and most informative of its observable parameters. Because of this, studying the periods of variable stars, and especially any changes in their periods, is an especially important part of the analysis of variable stars.

O–C

One very useful tool for finding period changes, and one which is very popular with astronomers, is to compute what is called "*O–C*" ("O minus C"). It is based on the following idea: if a star is perfectly periodic, then every period is exactly the same. In that case, we can predict its cycles in advance. If one maximum occurs on, say, JD 2,450,000, and the period is precisely 332 days (and never changes!), then the next maximum will occur on JD 2,450,332. This is not just guesswork: it is based on the way periodic systems behave. This is how scientific predictions are made: by combining a precise *theory* of behavior (perfect periodicity) with accurate parameters (the epoch, or time of maximum, and the period) determined from precise observations (made by careful variable star observers), we can predict the behavior of a star in advance. Then we can perform what may be the most powerful test in all of science: we can compare our predictions with future observations.

If the star is perfectly periodic, has a maximum at time t_o (the *epoch*), and the period is P, then we know that the *next* maximum will occur at time $t_o + P$. The next maximum after that will be at time $t_o + 2P$, then next at $t_o + 3P$, etc. In fact, if we choose t_o, our *epoch,* to be the time of maximum for cycle number *zero*, then the *computed time of maximum* for any cycle number n, which we can call C_n, is easy to calculate:

$$C_n = t_o + nP.$$

With this one formula, we can compute the times of all maxima, past, present, and future.

Of course, these times are correct only if the system is perfectly periodic. In addition to the computed times of maximum C_n, we can also directly observe the star to estimate the *observed time of maximum* for cycle number n, which we will call O_n. You have already done this in previous chapters, estimating the time of maximum either by eye, or by fitting a polynomial to the light curve data. We are now ready to compare theory (the computed times C_n) to observation (the observed times O_n), by simply taking the difference between the observed and computed times of maxima. These are the "*O–C*," or "observed minus computed" values. For each cycle number n, we have $(O–C)_n = O_n - C_n$. After we have determined the *O–C* values, we can plot *O–C* as a function of cycle number n. This gives us a powerful tool for period analysis: the *O–C diagram*.

Investigation 13.1: Constructing an *O-C* Diagram

Your teacher will assign you a system to observe by timing. For example, you may be asked to time when the street light changes from red to green, or when the next commercial starts on a TV show. What you will end up with are a set of observed times, the times at which the "important event" (whatever you are assigned to observe) has occurred. You should have observed ten occurrences (ten cycles) of this system.

1. Make a table to list all your observations, leaving space for 4 columns. Enter your actual observations in column 2.

2. Number your observations, starting with *zero* (astronomers and mathematicians often like to start numbering things at zero rather than one). These are the cycle numbers n for your observations. The observations themselves are the observed values O_n. Enter the cycle numbers in column 1 of your table. If you have observed 10 cycles, and start numbering them from zero, then your cycle numbers n will range from 0 to 9.

3. Take the observed time of your very first observation as the estimated epoch t_o.

4. Compute the difference between the first two observed times by subtracting the second from the first. Take this as your estimated period P.

5. Using your epoch t_o and period P, calculate the computed time C_n for each cycle you have observed. Enter these values in column 3 of your table.

6. For each cycle n, subtract the computed time C_n from the observed time O_n, which will give you the *O*\–*C* values. Enter these *O–C* values in column 4 of your table. **Note**: Because you took the first observation as your estimated epoch, the first *O-C* value will always be zero. Because you also took the time between the first two observations as your estimated period, the second *O–C* value will also always be zero.

7. Plot a graph with cycle number n on the x-axis and *O–C* value on the y-axis.

What does the *O–C* diagram tell you? Is this system perfectly periodic? Is your estimated period correct?

O–C Diagrams

To find out how *O–C* diagrams behave, let us construct some—for a set of six clocks. Actually, we will use seven clocks. One of them is a precise atomic clock, pre-set by the National Bureau of Standards. We will not actually test this clock, but rather we will use it to define the correct time. The other six are our "test clocks," and we will observe their behavior to construct *O–C* diagrams.

To create an *O–C* diagram, we need to define *C*, the computed time. So we will take as our *theory* that the test clocks are all perfectly periodic, with a *period* of 1 day, and that they are set correctly. Each day, we will observe the time at which our test clocks read "noon." We agree to take noontime on the first day of our test as the zero point of time (at which $t = 0$). In this case, when cycle zero begins, with each clock reading "noon" on our first test day, according to our theory it will actually be noon.

So the computed time of cycle 0 is $t_o=0$. This is the *epoch* of our theory. With an epoch $t_o=0$ and period $P=1$, we can calculate the computed times C_n for any cycle n. Since we are using the same theory, epoch, and period for every clock, the computed times C_n will be the same for each; they are listed in Table 13.1 on the next page. Also listed in Table 13.1 are the observations, the actual times at which each clock read "noon." For each observation, we have listed both the clock time and the time in days since the experiment began (which is what we will use to compute *O–C*).

Table 13.1

Computed and observed times of "noon" for six clocks

Observed Time

Cycle	*Computed*	Clock #1	Clock #2	Clock #3	Clock #4	Clock #5	Clock #6
0		12:00p	12:05p	12:00p	11:58a	12:00p	12:00p
	0	0	.0035	0	-.0014	0	0
1		12:00p	12:05p	12:03p	11:58a	11:58a	12:00p
	1	1	1.0035	1.0021	0.9986	0.9986	1
2		12:00p	12:05p	12:06p	11:58a	11:56a	12:01p
	2	2	2.0035	2.0042	1.9986	1.9972	2.0007
3		12:00p	12:05p	12:09p	11:58a	11:54a	12:03p
	3	3	3.0035	3.0062	2.9986	2.9958	3.0021
4		12:00p	12:05p	12:12p	12:37p	11:52a	12:06p
	4	4	4.0035	4.0083	4.0257	3.9944	4.0042
5		12:00p	12:05p	12:15p	12:37p	11:50a	12:10p
	5	5	5.0035	5.0104	5.0257	4.9931	5.0069
6		12:00p	12:05p	12:18p	12:37p	11:51a	12:15p
	6	6	6.0035	6.0125	6.0257	5.9938	6.0104
7		12:00p	12:05p	12:21p	12:37p	11:52a	12:21p
	7	7	7.0035	7.0146	7.0257	6.9944	7.0146
8		12:00p	12:05p	12:24p	12:37p	11:53a	12:28p
	8	8	8.0035	8.0167	8.0257	7.9951	8.0194
9		12:00p	12:05p	12:27p	12:37p	11:54a	12:36p
	9	9	9.0035	9.0188	9.0257	8.9958	9.0250

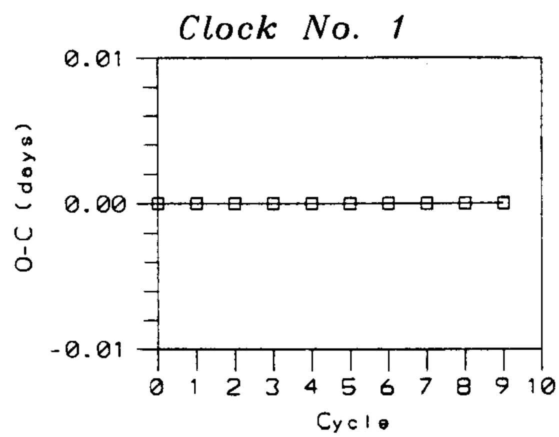
We see that Clock No. 1 fits our theory: when it reads noon, it actually is noon. Clock No. 2 is late, not reading noon until 12:05pm every day. Clock No. 3 is slow: it indicates "noon" 3 minutes later every day. Clock No. 4 is a little early until day 4, and a lot late after that. Clock No. 5 at first runs fast, marking "noon" two minutes earlier each day, until day 6; from then on it runs slow, marking "noon" a minute later every day. Clock No. 6 is not only slow, it is getting slower every day. It is easy to translate these into *O–C* values simply by subtracting *C* from *O*; these are listed in Table 13.2. We have used them to plot *O–C* diagrams in Figures 13.1a–f.

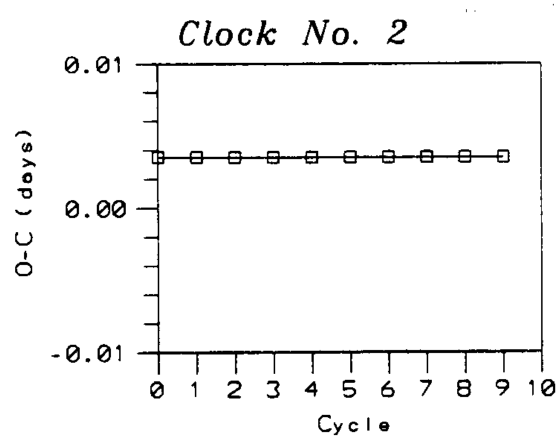
Table 13.2: *O–C* Values for Six Clocks

Cycle Number	Clock#1	Clock#2	Clock#3	Clock#4	Clock#5	Clock#6
0	0	.0035	.0000	-.0014	.0000	.0000
1	0	.0035	.0021	-.0014	-.0014	.0000
2	0	.0035	.0042	-.0014	-.0028	.0007
3	0	.0035	.0062	-.0014	-.0042	.0021
4	0	.0035	.0083	.0257	-.0056	.0042
5	0	.0035	.0104	.0257	-.0069	.0069
6	0	.0035	.0125	.0257	-.0062	.0104
7	0	.0035	.0146	.0257	-.0056	.0146
8	0	.0035	.0167	.0257	-.0049	.0194
9	0	.0035	.0188	.0257	-.0042	.0250

The first diagram (Clock No. 1, Figure 13.1a) shows what *O–C* looks like when our theory is exactly correct. All the *O–C* values are zero, because theory matches observation.

In the next diagram (Clock No. 2, Figure 13.1b), the *O–C* values still fall on a straight line parallel to the *x*-axis. However, they are all "off," by the same amount. Clock No. 2 keeps good time (it indicates noon at the same time every day), but it is a little late. In this case the theory is correct: it is perfectly periodic, and the period is correct in that it cycles in precisely 1 day; but the *epoch* is not correct—it is not "set" properly. It actually has its time of cycle zero at $t_o=0.0035$. So we have our first clue from an *O–C* diagram: **when the *O–C* values lie on a straight line which is horizontal** (parallel to the *x*-axis)**, but are all displaced from 0 by the same amount, the system is periodic, and our period is correct, but the epoch is wrong**.





Figures 13.1a (top) & 13.1b (bottom)

The next clock (Clock No. 3, Figure 13.1c) keeps indicating "noon" later and later every day. In fact, it says "noon" 3 minutes later each day. Clock No. 3 is just slow: instead of cycling in 1 day like a good clock should, it cycles in 1 day 3 minutes = 1.0021 days. Our theory is still correct in that it appears to be perfectly periodic. Our epoch is also correct: cycle 0 really did start at time 0. But the period is wrong: the true period is not *P=1* day, but *P=1.0021* days. This gives our next clue to look for in an *O–C* diagram: **when the *O-C* values lie on a straight line, but the line is not horizontal, the system is periodic but our estimated period is not correct**.

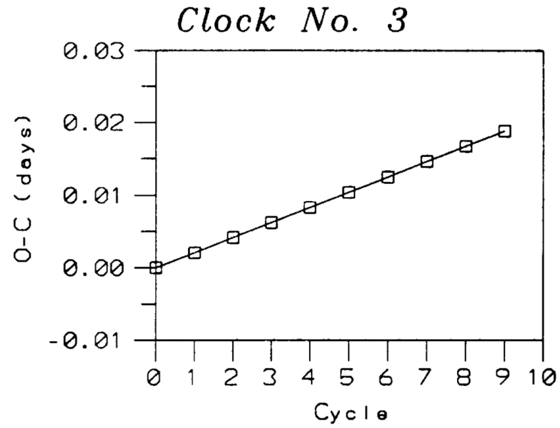


Figure 13.1c

The true period of Clock No. 3 is longer than the estimated period by 3 minutes = 0.0021 day. If we draw a straight line through the *O–C* values in Figure 13.1c, that line has a slope of 0.0021 day/cycle. Now we have another clue from *O–C*: **when the system is periodic but our period is not correct, the slope of the line through the *O–C* values is the difference between the true and estimated periods. In addition, the intercept of the line is the difference between the true and estimated epochs**.

Clock No. 4 (Figure 13.1d) was 2 minutes early until day 4, after which it was 37 minutes late. It kept good time most days, cycling in 24 hours, except from day 3 to 4, when it took an extra 39 minutes. It turns out that someone unplugged Clock No. 4 for 39 minutes between days 3 and 4. After that, the clock still has the correct period, but it is no longer set even close to being correct. In effect, it has been "re-set" by being turned off: the *epoch* has changed. Here is yet another clue from any "broken" line in an *O–C* diagram: **when the *O–C* values leave one straight line, and start another with the same slope, but which is offset, the period has remained the same but the epoch has changed**.

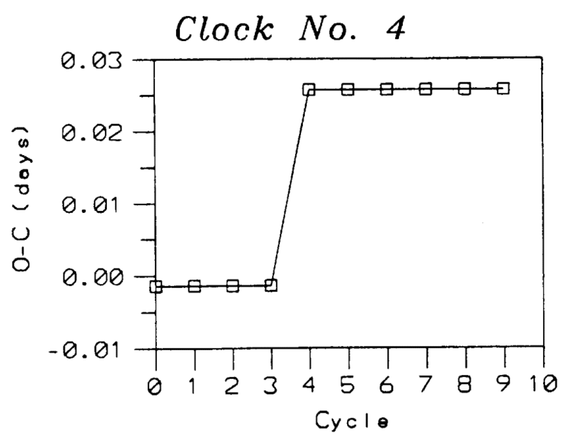


Figure 13.1d

Clock No. 5 (Figure 13.1e) was fast through day 5, reading "noon" two minutes earlier every day. This is a case of *O–C* values following a straight but not horizontal line, so the period is not correct. During these first 5 days, the period was 2 minutes less than a day, or 0.9986 day. From then on, Clock No. 5 cycled a minute later every day. The *O–C* diagram shows *another* straight line, with a different slope; this indicates a *new* period, which is 1 minute longer than a day, or 1.0007 days.

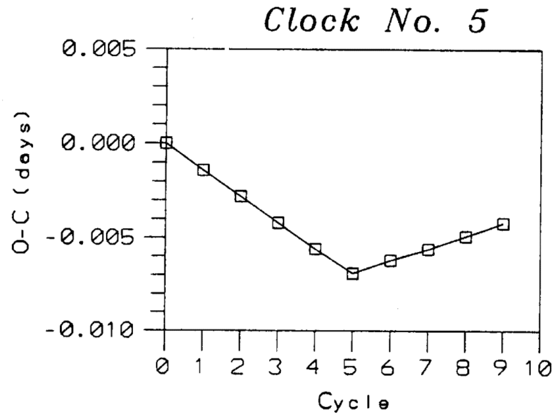


Figure 13.1e

This gives us one of the most important clues to look for in *O–C* diagrams: **when the *O–C* values change from one straight line to another which has a different slope, the period has changed. The slope of each line is the difference between its period and the estimated period**.

Clock No. 6 (Figure 13.1f) is running later and later every day, and not by the same amount. The first day it is fine, but the next day it loses 1 minute, then it loses 2 minutes, then 3, etc. This clock is *not* perfectly periodic: its period is different every day. This also gives us one of the most important things to look for in *O–C* diagrams: **when the *O–C* values do not follow a straight line, the system is not perfectly periodic**.

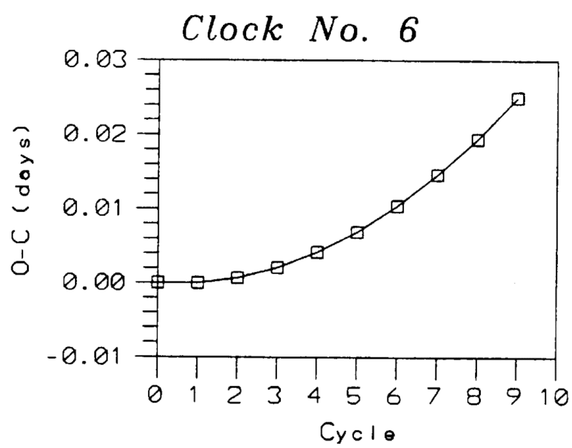


Figure 13.1f

These simple clock examples illustrate how *O–C* diagrams reveal important changes in period and epoch.

For real data, things are not always so simple. Many systems are not perfectly periodic. For Mira-type variables, for example, the period of each cycle is a little different, although the average period is stable. And for all real data, there are observational errors, no matter how precise the instrumentation. Now let us look at some real-life examples.

***O–C* Diagram Relationships**

Study the following *O–C* diagram for the Mira-type variable Z Tau (Figure 13.2). At first, the observed period is longer than the estimated period, so the *O–C* values get higher and higher. Later, the period shortens, so that near the end of the graph the *O–C* values are getting lower and lower.

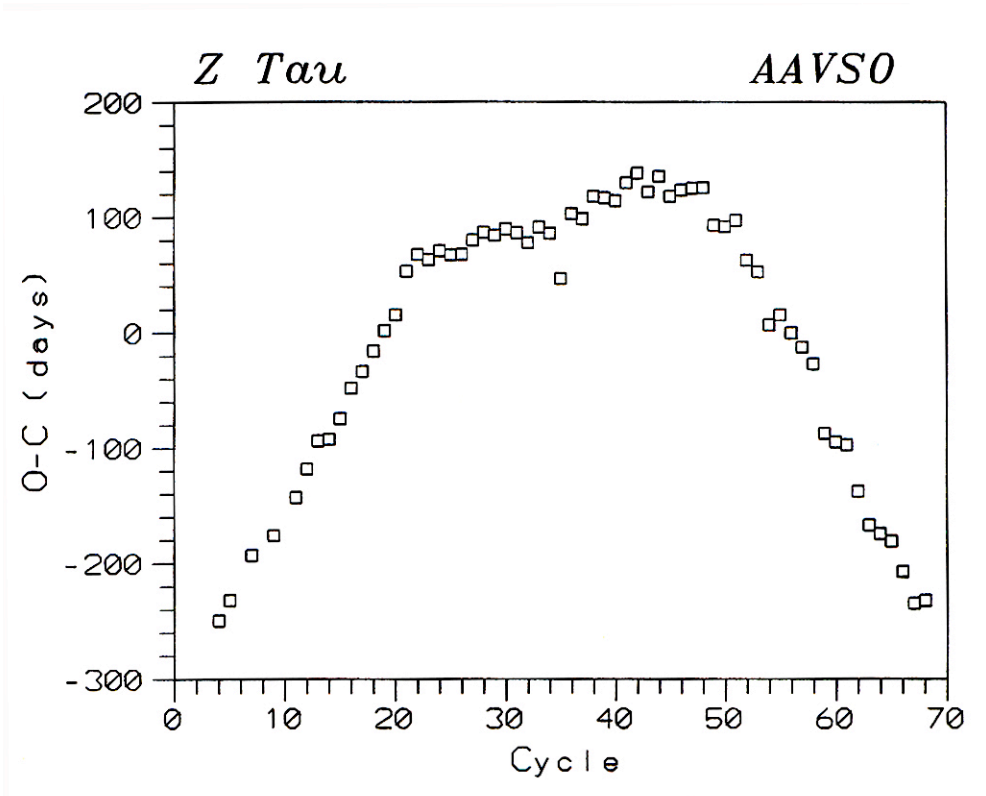


Figure 13.2

At first glance, it appears that the period of Z Tau changed slowly but steadily, decreasing by the same amount every cycle. This is similar to the behavior of Clock No.6 in our clock example. If this were the case, then the *O–C* values would fall along a parabola, which is plotted as a dashed line in Figure 13.3 on the following page. Upon closer examination, however, it is seen that a better explanation of Z Tau's behavior might be two distinct changes in period. These are plotted as solid lines in Figure 13.3 on the following page. If this interpretation is correct, then each line segment represents a different period. For the first line, from cycle 4 to about cycle 20, the slope is positive, so the period is longer than the estimated period. For the second line, from about cycle 20 to about cycle 50, the slope is also positive, but much smaller; again, the period is longer than the estimated period, but only slightly. For the last line, from about cycle 50 to the end, the slope is negative, so the period is less than the estimated period.The *O–C* diagram shows three different periodicities for Z Tau, with the observed maxima occuring from ~240 days earlier than calculated to ~140 days later than calculated.

More detailed statistical inspection of the graph shows that the *O–C* values fit the three straight lines better than they fit the parabola. So the data indicate that Z Tau has indeed shown three distinct periods, represented by the three straight lines, rather than a smoothly-changing period indicated by the dashed line.

It is also worth noting that the *O–C* values lie near to, but not exactly on, straight lines. This is to be expected; all *real* data have random errors. Also, the period of Z Tau may actually be a little different from cycle to cycle, although the average period seems to be constant over many cycles.

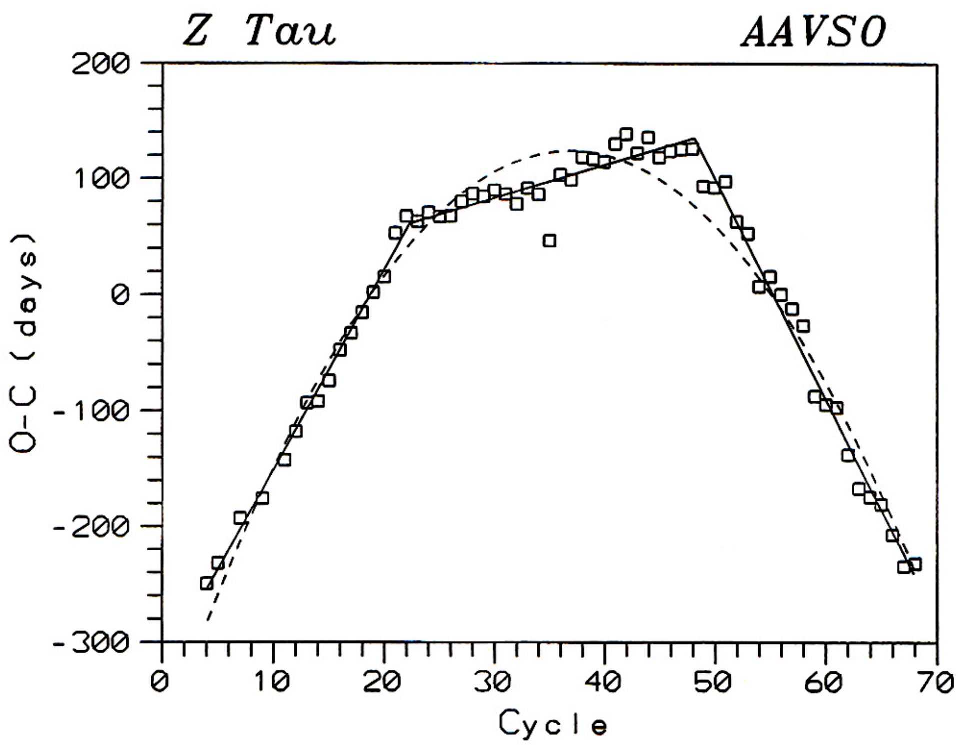
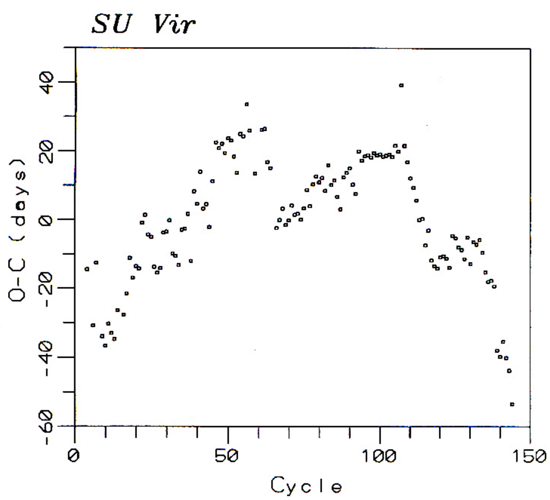
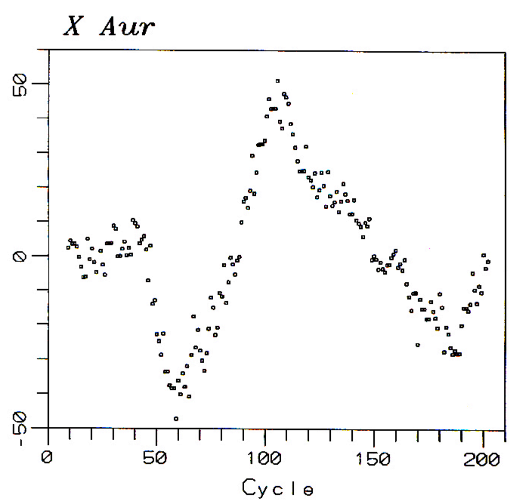


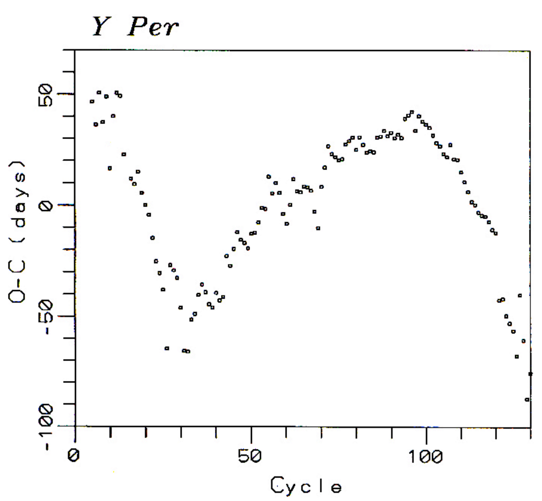
Figure 13.3

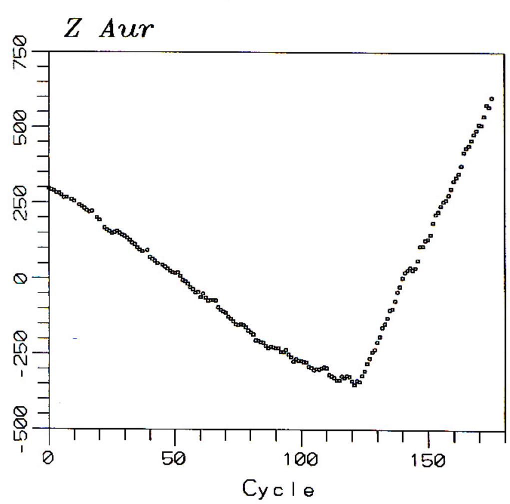
Core Activity 13.2: Understanding *O–C* with Miras

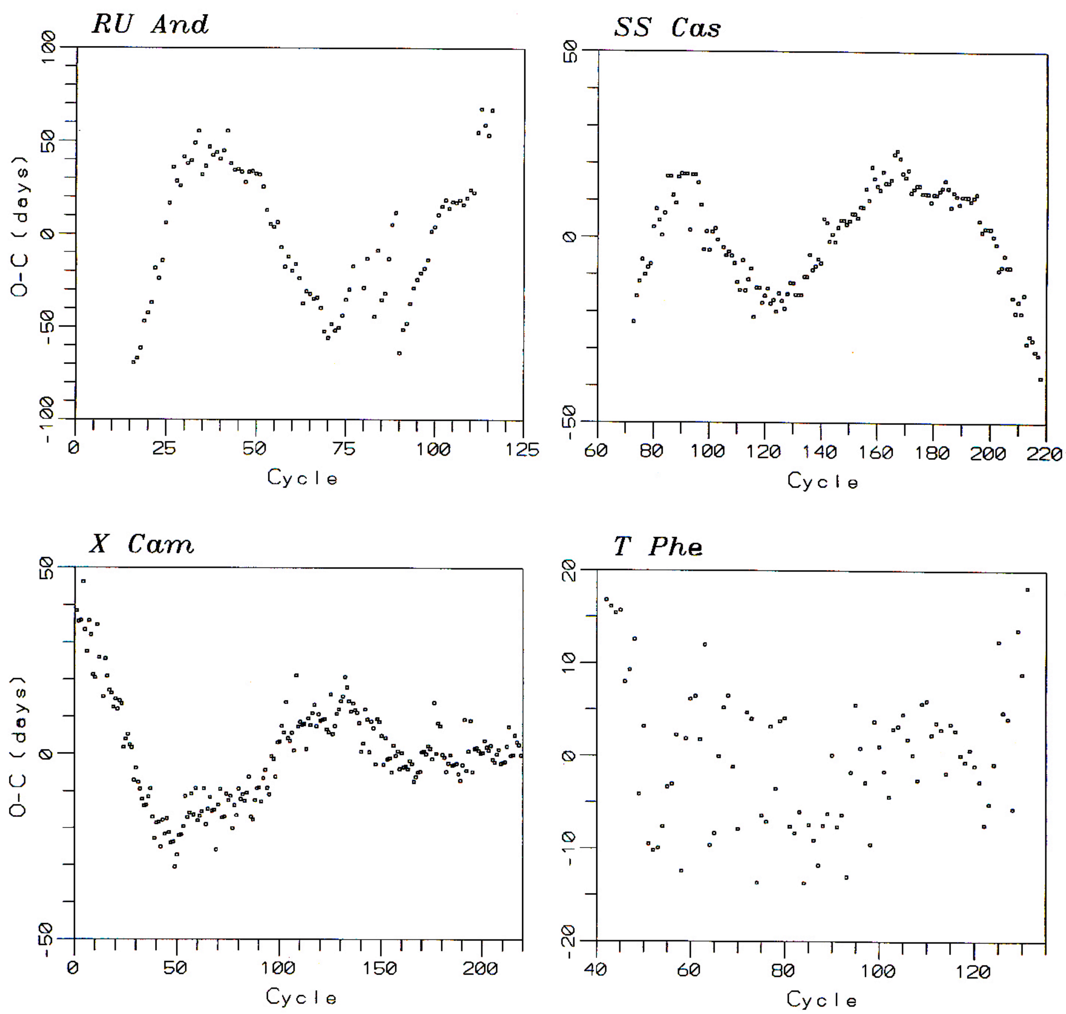
The following *O–C* diagrams have been obtained by studying the long-term behavior of eight Mira-type variable stars. Study the *O–C* diagrams and describe the differences between the predicted and observed behaviors of these stars relative to epoch and/or period.










RU And
O-C (days)
100
50
0
-50
-100
0
25
50
75
100
125
Cycle
SS Cas
50
0
-50
60
80
100
120
140
160
180
200
220
Cycle
X Cam
O-C (days)
50
0
-50
0
50
100
150
200
Cycle
T Phe
20
10
0
-10
-20
40
60
80
100
120
Cycle

Core Activity 13.3: Prediction of SS Cyg

Look at the following light curve for the eruptive variable SS Cyg (Figure 13.4). Estimate the time of beginning of each eruption, the amplitude in magnitudes, and the duration in days. Predict the time of the next eruption. Access VSTAR to plot the observations for SS Cyg for JD 2449500 through 2449950. Does your predicted time for the next eruption agree with the actual time of outburst?

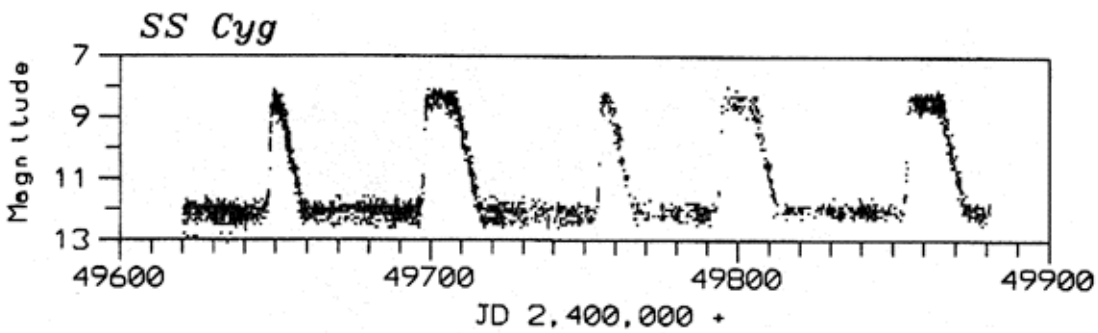


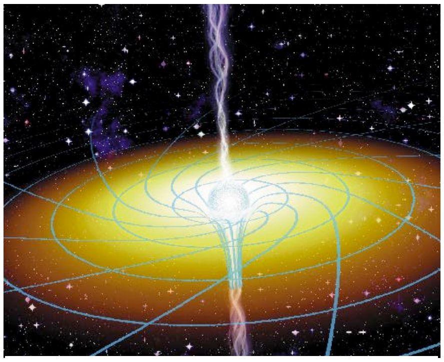
Figure 13.4

Activity 13.4: Prediction and Observation of Delta Cep

If you have observed delta Cep and determined your best estimate of the period by plotting a phase diagram, predict the times for the next few maxima. Observe delta Cep for the required amount of time and plot an *O–C* diagram for your predicted and observed results. If the diagram shows all of your *O–C* data points clustered near the 0 line on your graph, then your period determination was accurate. If you continued to observe delta Cep and noticed any changes, then the reason would be that delta Cep's period was changing.

It would be helpful at this point to write a general formula which would predict the times of maxima for delta Cep. This type of formula is called an *ephemeris* (plural: *ephemerides*) of the stars. With the formula, write a calculator or computer program to calculate the predicted times of maxima. You could write the program so that it only produces times of maxima which occur between 9:00 PM and midnight, standard time, at your location; you could also incorporate the decimal portion of the JD which corresponds to these times in your formula.

Universal Models



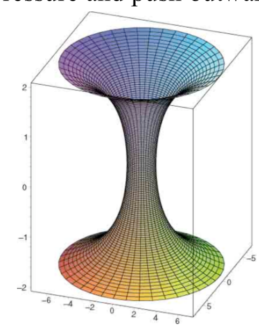
Frame Dragging – illustration courtesy of the Gravity B Probe

Cosmology is the study of the origin, evolution, and large-scale structure of the universe. Cosmological models are possible representations of the universe in simple terms. A basic assumption of cosmology is the cosmological principle. The principle states that there are no preferred places in the universe, that the universe is isotropic and homogenous. Isotropy is the property by which all directions appear indistinguishable to an observer expanding with the universe. In other words, neglecting local irregularities, measurements of the limited regions of the universe available to Earth-based observers are valid samples of the whole universe. Models are an essential link between observation and theory and act as the basis for prediction. A simple model for a two-dimensional universe is the surface of an expanding balloon, on which may be demonstrated Hubble's Law and the isotropy of the microwave background radiation, the heat left over from the explosion that initiated the universe.

Most standard cosmological models of the universe are mathematical and are based on the Friedmann universe, which assumes homogeneity and isotropy of an expanding (or contracting) universe in which the only force that need be considered is gravitation. The big bang theory is such a model. These models result from considerations of Einstein's field equations of general relativity. When the gravitational force is negligible, the equations reduce to $(dR/dt)^2/R^2 + kc^2/R^2 = (8/3)G\rho$ for energy conservation. This is known as the Friedmann equation, and ρR^3 is constant for mass conservation. R is the cosmic scale factor, ρ the mean density of matter, G the gravitational constant, and c the speed of light; k is the curvature index of space with values of +1 (closed universe in which the expansion stops, the universe contracts, and ends with a big crunch), –1 (open universe in which the expansion constantly slows down but never stops), or 0 (flat or Einstein-de Sitter universe.) Other models involving the cosmological constant, Λ, have been proposed, such as the de Sitter model, in which no mass is present; the Lemaitre model, which exhibits a coasting phase during which R is roughly constant; the steady-state theory for an unchanging universe; and those in which the gravitational constant, G, varies with time (Brans-Dicke theory). The cosmological constant is an arbitrary constant. Although it is possible for it to have any value that does not conflict with observation, it is highly probable that it is close to zero. Cosmological models involving Λ are considered nonstandard. In the standard (Friedmann) models, $\Lambda = 0$.

The Brans-Dicke theory is a relativistic theory of gravitation and a variation of Einstein's general theory of relativity. It is considered by many astronomers to be the most serious alternative to general relativity. Newton's gravitational constant is replaced by a slowly varying scalar field. The effect is to allow the strength of gravity to decrease with time. In the limit that this variation is zero, the various Brans-Dicke theories of gravitation that now exist reduce to Einstein's general relativity. Current observations limit the variation of Newton's gravitational constant to be less than one part in 10^{10} per year. This means that for local applications of a non-cosmological nature, the Brans-Dicke theory is indistinguishable from general relativity. Another model of the early universe is the inflationary universe proposed by Alan Guth in 1980. This theory describes a possible phase in the very early universe when its size increased by an extraordinary factor, perhaps by up to 10^{50}, in an extremely short period. At an age of 10^{-35} seconds, the state of the universe had to change, as the electromagnetic and strong nuclear forces "froze out" into different values. The energy released by this phase change is calculated to have caused the universe to expand, or inflate, catastrophically. The inflationary phase ended at some time before 10^{-30} seconds. After this time, the inflationary model coincides with the standard big bang description of the universe. The inflationary phase means that the observed universe is only a very small fraction of the entire universe. In addition, distant parts of the universe would have been much closer in the period before inflation than has been previously considered. The theory can explain the isotropy of the microwave background radiation, which requires distant parts of the universe to have been in causal contact in the past.

In the solution for Einstein's equations for extreme curvature of spacetime, a passage can exist between two universes or between two parts of the same universe. This structure is called an Einstein-Rosen bridge, or wormhole. Such bridges theoretically can occur in black holes for brief moments in time. Just before or just after that moment, there is no passage, only the singularity of the black hole. If you tried to race through the wormhole in the instant it opened at anything less than the speed of light, the wormhole would snap shut, trapping you and sending you into the singularity to be torn into subatomic particles, fried by radiation and crushed to infinite density. One solution to holding the wormhole open is what physicists refer to as "exotic matter." Ordinary matter has finite energy and exerts finite pressure and creates a normal, pulling, gravitational field. The opposite would be matter that has negative energy and exerts negative pressure to such an extreme level that it would produce "antigravity." Whereas ordinary matter pushes outward with pressure and pulls inward with gravity, exotic matter would pull inward with its pressure and push outward with its gravity. This concept would be similar to the inflationary universe theory. During the inflationary phase the universe underwent a rapid expansion that led to its current size and smoothness. The condition responsible for inflation is known as a false vacuum. This was the brief state of the universe when the electromagnetic and nuclear forces were indistinguishable from one another. Although not exotic matter, the false vacuum exerted a negative pressure and a repulsive gravitational field. The exotic matter necessary to create a stable wormhole would have to display the same characteristics as the false vacuum, but to a much larger degree. An Einstein-Rosen bridge could be coated with exotic matter and stabilized, maybe even become permanent.



What would a wormhole look like? It might appear spherical from the outside. The boundary would not necessarily look black, like a black hole, even though the outer structure of their spacetime geometries is similar. A black hole has an event horizon from which nothing can escape. However, you can see through a wormhole to the outside at the opposite end. Upon entering you would travel to the center of the sphere and eventually find yourself traveling away from the center, to emerge in another place outside of the wormhole. Inside the wormhole, you would be able to see light coming in from the normal space at either end of the wormhole; however, the view to either side would be distorted. The space is extremely curved. Light heading off in any direction perpendicular to the `radius' through the center of the wormhole would travel straight in the normal space inside, but end up back where it started, like a line drawn around the surface of a sphere. If you faced sideways in a wormhole you could, in principle, see the back of your head. However, the light would be distorted and your view out of focus. You would not be able to see stars through the sides of the tunnel because there is no literal tunnel wall and inside the light is trapped by the extreme curvature of space. You would not be able simply to travel through the mouth of the tunnel. It is not shaped like a funnel as represented in the two-dimensional models of the three-dimensional space around a wormhole drawn above. In these models, a circle in two-dimensional space is the analog of a sphere in three-dimensional space, and the real curved space around a wormhole is represented by a stretched two-dimensional space that resembles a funnel. You would not be able to travel through the mouth of the funnel. The funnel is a three-dimensional hyperspace in the two-dimensional analog. You would have to crawl along the surface of the two-dimensional space to get the true meaning of the nature of that space and some feeling for the three-dimensional reality. Another consideration for wormholes is Hawking radiation. Stephen Hawking's calculations show that in the space near the event horizon of a black hole, natural radiation is emitted which eventually leads to the evaporation of the black hole. In a wormhole, the Hawking radiation from one end of the wormhole can travel through normal space to the other end, enter, travel straight through, and emerge just as it left. Now there is twice as much radiation. This cycle could repeat endlessly, building up an infinite energy density which would either seal off the wormhole or prevent it from having existed in the first place.

So far there is no grand unified theory in physics. The holy grail of physics is the quest for a theory which unifies the physics of extremely curved spacetime with the probabilistic nature of quantum mechanics. This theory is necessary to fully understand the nature of the singularity of a black hole, the origin of the universe, and the validity of other mathematical cosmological models such as Einstein-Rosen bridges.

Core Activity 13.5: Prediction and Analysis of the Period of R Cyg

Access the VSTAR database and load the following observational data for R Cyg (Figure 13.5) on your screen. Determine the times of maximum brightness by fitting a polynomial to the observations. Your instructor will give you the times of predicted maxima. Plot an *O–C* diagram and determine the difference between the predicted and observed behavior for R Cyg. What is the star's behavior? Can you find any secondary relationships in the period of this pulsating red giant star?

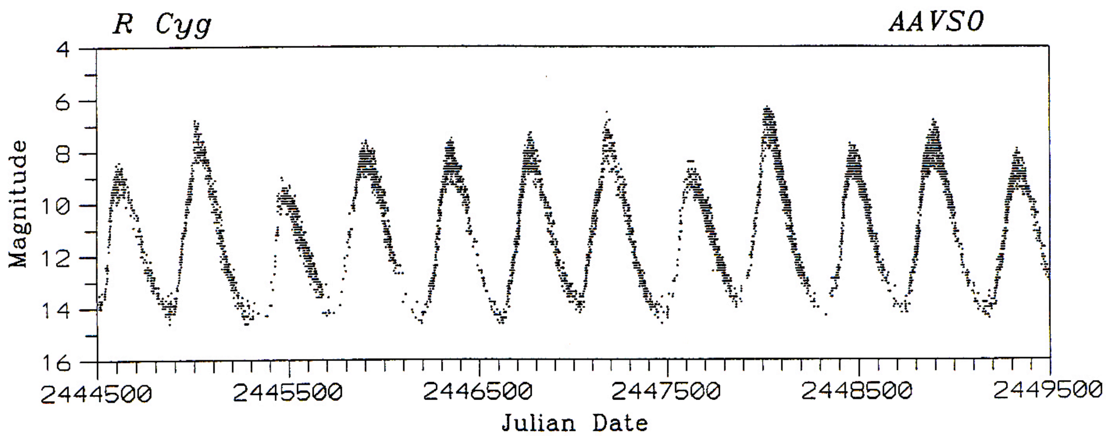


Figure 13.5

Activity 13.6: *O–C* for Eclipsing Binary Stars

You have studied pulsating variables, both short-period Cepheids such as delta Cep and long-period Miras such as V Cas. Now we will use *O–C* to study the behavior of an eclipsing binary star. Remember that for eclipsing binaries, it is the time of *minimum* brightness, rather than maximum, that is of most interest. This is because minimum corresponds to the middle of the eclipse, and the eclipse is what we are really interested in timing. In fact, a large number of variable star observers specialize in eclipsing binary stars, and design their observing programs to get accurate timings of the minimum brightness. Table 13.9 lists AAVSO data for the eclipsing binary star X Tri. Instead of containing magnitudes, it lists times of minima.

Let's construct an *O–C* diagram for the minima of X Tri. To do so, we need to estimate the period and the epoch. We will use the following values:

Epoch: t_o = JD 2442502.721

Period: P = 0.975352 day

Using this period and epoch, we can calculate the computed time C_n of any minimum.

There are a lot of minima in Table 13.9 (on the following page). Your teacher will assign each of you a small number of cycles to compute. For the cycles assigned to you, take the cycle number n and use it to calculate the computed time of minimum C_n. When all the students have completed the cycles assigned to them, collect all the class data into a large table, listing cycle number n (from Table 13.9), observed time of minimum O_n (also from the Table 13.9), and your computed time C_n.

Now subtract C_n from O_n, for each cycle, to get $(O–C)_n$ for every cycle n listed in the table. Finally, prepare an *O–C* diagram, showing cycle number n on the x-axis and *O–C* value on the y-axis.

What can you tell about the behavior of X Tri from this *O–C* diagram? Are the estimated period and epoch correct? Did the period change?

Table 13.9
Minima Timings of X Tri[1]

Cycle[2]	JD (minimum)	Cycle[2]	JD (minimum)	Cycle[2]	JD (minimum)
230	2442726.175	3197	2445608.722	5107	2447464.348
318	2442811.668	3198	2445609.694	5108	2447465.310
322	2442815.551	3233	2445643.695	5168	2447523.601
523	2443010.832	3233	2445643.697	5169	2447524.576
524	2443011.802	3508	2445910.867	5200	2447554.687
524	2443011.806	3544	2445945.845	5202	2447556.637
524	2443011.811	3619	2446018.711	5237	2447590.644
557	2443043.863	3621	2446020.646	5238	2447591.611
560	2443046.783	3621	2446020.649	5446	2447793.689
564	2443050.666	3621	2446020.652	5447	2447794.661
567	2443053.582	3622	2446021.618	5447	2447794.667
945	2443420.818	3622	2446021.618	5448	2447795.639
948	2443423.741	3622	2446021.620	5449	2447796.604
952	2443427.615	3626	2446025.508	5477	2447823.805
984	2443458.717	3659	2446057.567	5478	2447824.776
985	2443459.687	3660	2446058.540	5481	2447827.690
985	2443459.689	3690	2446087.686	5516	2447861.695
1020	2443493.687	3725	2446121.692	5520	2447865.581
1021	2443494.658	3934	2446324.737	5555	2447899.589
1262	2443728.797	3936	2446326.679	5829	2448165.784
1338	2443802.635	3974	2446363.599	5903	2448237.677
1408	2443870.641	4003	2446391.772	5903	2448237.677
1686	2444140.727	4004	2446392.745	5942	2448275.566
1687	2444141.700	4008	2446396.633	6180	2448506.792
1688	2444142.671	4042	2446429.665	6570	2448885.692
1689	2444143.641	4044	2446431.605	6573	2448888.606
1760	2444212.623	4078	2446464.635	6608	2448922.610
1762	2444214.566	4079	2446465.612	6637	2448950.781
1795	2444246.628	4322	2446701.688	6639	2448952.724
1797	2444248.567	4354	2446732.781	6641	2448954.668
1829	2444279.660	4356	2446734.726	6642	2448955.638
2075	2444518.656	4358	2446736.671	6957	2449261.673
2077	2444520.602	4389	2446766.785	7031	2449333.558
2112	2444554.600	4391	2446768.728	7348	2449641.535
2182	2444622.609	4397	2446774.559	7728	2450010.717
2419	2444852.863	4432	2446808.560	7734	2450016.550
2452	2444884.926	4668	2447037.839	7763	2450044.721
2527	2444957.790	4740	2447107.788	7764	2450045.693
2566	2444995.678	4741	2447108.761	7769	2450050.555
2845	2445266.743	4742	2447109.735	7800	2450080.669
2878	2445298.797	4742	2447109.735		

[1]Times of minima of X Tri are from AAVSO monographs *Observed Minima Timings of Eclipsing Binaries, Nos. 1,2,3,* prepared by M. Baldwin and G. Samolyk (1993, 1995, 1996).

[2]Repeated cycles indicate times of minimum from different observers.

SPACE TALK

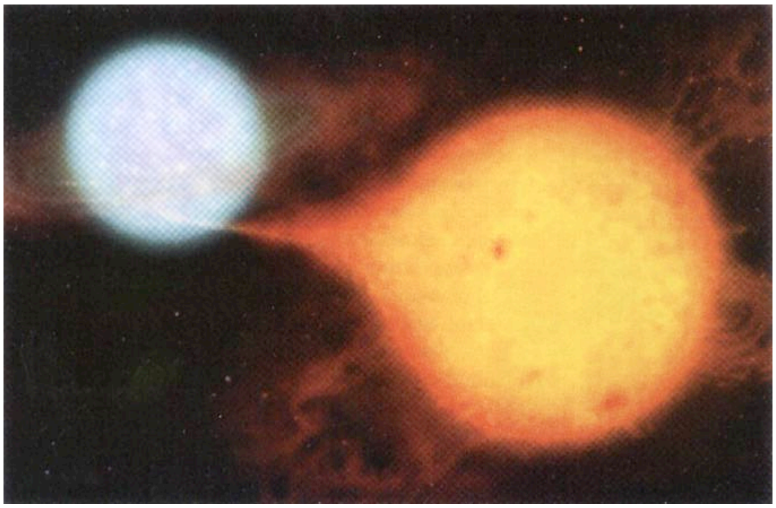
Algol (beta Persei) is the brightest eclipsing binary in the sky, and the most famous of the eclipsing variable stars. Algol means "Demon Star" in Arabic, and this suggests that its strange variability might have been known in antiquity, although there is no concrete evidence to support this conjecture. The name is from the Arabic *Al Ra's al Ghul*, which translates to "The Demon's Head." The Hebrews called the star "Satan's Head." In some other traditions, it is identified with the mysterious and sinister Lilith, the legendary first wife of Adam. Medieval astrologers considered Algol the most dangerous and unlucky star in the heavens.

Although Algol's name suggests that its light changes were known to the medieval Arabs, the first written account was made by the Italian astronomer Geminiano Montanari of Bologna in 1667. The English astronomer John Goodricke is credited with establishing the period of Algol in 1782. Goodricke proposed that the variation in Algol's brightness was due to its being eclipsed by an unseen companion, possibly a planet. In 1881, Edward Pickering, the Director of Harvard College Observatory, presented evidence which showed that Algol was an eclipsing binary star.

One peculiar feature of the Algol system, shared by other binaries of the same type, is that the fainter and less massive star has evolved to the subgiant stage, while the primary star remains a main sequence object. This is a stellar evolutionary paradox, for if the stars are of the same age, the brighter and more massive star should evolve more rapidly. Binary stars form together from the same condensing cloud of gas and dust, and therefore have to be the same age. Astronomer Fred Hoyle suggested the following solution to the dilemma. The fainter star was originally the more massive and luminous of the pair. As it began its evolutionary expansion it lost great quantities of matter to the close companion. It thus became fainter as it evolved to the subgiant stage. At the same time the companion grew more brilliant as the result of its increased mass. This is now considered to be the case. Although Algol is the most studied eclipsing binary, high-resolution spectroscopy has only recently begun to reveal the details of its behavior.

Algol is actually a three-star system 92 light-years away. The **primary** star is a bright B8 main-sequence star. The primary is eclipsed every 2.87 days by the **secondary** star, a larger, dimmer, less massive K2 subgiant with a very active surface covered with starspots. The K2 subgiant and the B8 primary are in a very close orbit. In the distance a **tertiary** F1 main-sequence star orbits the binary pair every 1.86 years. Algol varies in magnitude from 2.1 at maximum to 3.4 at primary minimum, with a period of 2.87 days. The period is slowly lengthening due to the mass transfer of material between the two stars. The primary eclipse occurs when the fainter K2 secondary passes in front of the brighter B8 star, and lasts for ~10 hours. To us, the eclipse is a partial one, due to the angle from which we observe it. There is also a shallow secondary eclipse when the B8 star passes in front of the K2 star. This can only be detected photoelectrically. The primary eclipse, however, can easily be detected with the unaided eye.

The K2 subgiant has expanded to fill its **Roche lobe**, a teardrop-shaped volume of space in which its gravity is strong enough to hold onto its loose atmospheric material. The tip of the teardrop shape points in the direction of the primary. As the K2 subgiant tries to expand further, a thin but powerful stream of gas spills from the point of the Roche lobe and crashes down onto the B8 primary star. A binary system such as this, in which one component has filled its Roche lobe and is transferring material to its companion, is called a **semidetached binary**. The speed of the stream of gas is 520 km/s when it slams into the B8 star. The stream of gas, now heated to 100,000K, strikes the B8 star's surface at a low angle and kicks a spray of gas forward and upward. This spray forms a variable, asymmetric **accretion disk** that circles the primary before settling onto the surface. The disk varies in size and shape, indicating that the gas stream varies also. The K2 star must overflow intermittently. If the B8 star were smaller, or if the stars' separation were wider, there would be room for the formation of a permanent, stable accretion disk. Instead, the surface of the B8 star gets in the way. Algol-type binaries with orbital periods greater than 5 or 6 days do have room to acquire permanent accretion disks, but Algol itself revolves in only 2.87 days.



Algol is a strong radio source. The radio emissions come from the hot corona, the layer of atmosphere directly above the photosphere surrounding the K2 star. The star probably rotates in step with its orbital period, generating a strong magnetic dynamo effect within the star, intense surface activity, and a strong radio-emitting corona. This was confirmed by **very long baseline interferometry** (**VLBI**), a method of simultaneously pointing several radio telescopes (widely separated by long distances) at an object. Radio astronomers also announced that the orbital plane of the close binary pair is oriented at a right angle to the orbital plane of the distant F1 star, contrary to theories relating to the formation of multiple star systems. Another study has reported the opposite—that all three stars lie in the same orbital plane.

In September 1990, the second-brightest eclipsing binary was discovered, and it happens to be located in the same constellation. The star is 3rd magnitude gamma Persei. The eclipses of gamma Persei occur rarely—approximately every 14.67 years. The next eclipse is expected in April of 2005. However, the star will then be in superior conjunction with the Sun, and so will not be visible from Earth. (Objects are in **superior conjunction** when they are on the opposite side of the Sun from the Earth.)

Gamma Persei consists of a cool, giant G8 primary star in orbit with a hot, main-sequence A2 secondary. It is a **composite-spectrum binary** (also called a spectroscopic binary): spectroscopic analysis shows the presence of features from two different stars. The composite nature of the spectrum was recognized in 1897 by Antonia Maury at Harvard. Gamma Persei was resolved into its two components for the first time in 1973, and it was extensively analyzed in 1987. At this time it was predicted that the A2 star would pass behind the G8 star in the fall of 1990. The eclipse occurred on the evening of September 12th, and was recorded at several observatories. The secondary star "set" more or less vertically behind the giant star's limb, so the eclipse was central, or behind the middle of the G8 star, and lasted for an entire week. The eclipse was 0.3 magnitude deep visually, so it was detectable—though certainly not conspicuous—with the unaided eye. Gamma Persei will not eclipse again for unaided-eye observers until November 2019.

THE BIRCH STREET IRREGULARS:

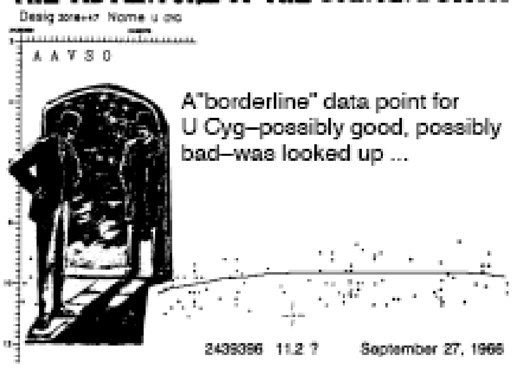
MYSTERIES FOUND AND RESOLVED IN THE AAVSO DATA ARCHIVES

by Sara J. Beck, Michael Saladyga, Janet A. Mattei and the AAVSO Technical Staff

(Adapted from a paper given at the 1994 AAVSO Spring meeting.)

As AAVSO data are evaluated, AAVSO Technical staff and the Director run across several kinds of errors which are tracked down and rectified–a process requiring skillful investigative techniques, a good head for deduction, and dogged tenacity. With apologies to Sir Arthur Conan Doyle, author of Sherlock Holmes, here are a few of the many success stories of the detectives known as the Birch Street Irregulars. These cases also provide the new observer with an idea of some of the common pitfalls experienced by their predecessors.

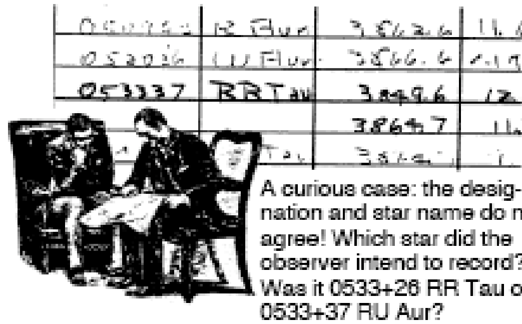
THE ADVENTURE OF THE DANCING DATA



A check on the observer's report showed that the Julian Dates for not only U Cyg, but for the entire report, were off by more than 300 days compared to the month and year written in the header.

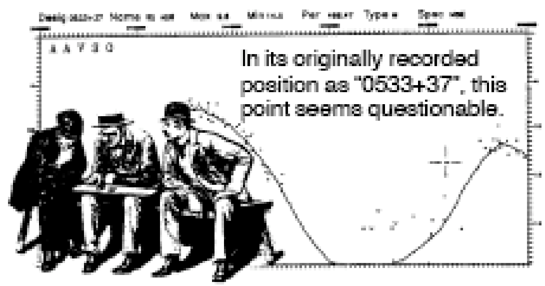
In comparing the JD calendars for the year of the report and the previous year, it became obvious that the observer had copied the JDs from the previous year's calendar.

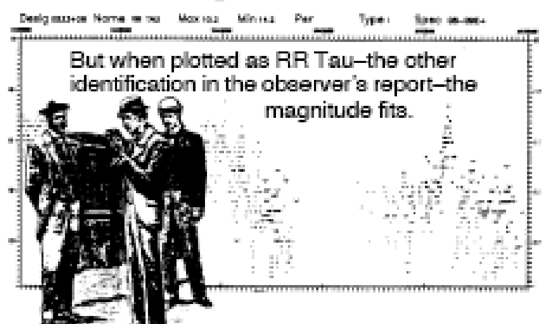
A CASE OF IDENTITY



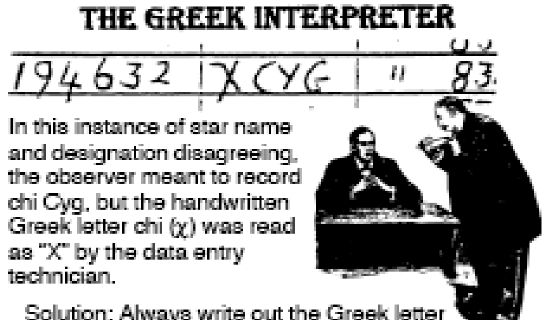
A curious case: the designation and star name do not agree! Which star did the observer intend to record? Was it 0533+26 RR Tau or 0533+37 RU Aur?

The problem: many observations in the archives were recorded with a name and designation for two different stars. The usual causes include: (1) The observer reading the designation or name from the line above in the report form; (2) giving the wrong component letter, or none at all, in the designation; or (3) simply writing one star's name while thinking of another star (for example, WX Cet and WX Cyg).





THE ADVENTURE OF THE GREEK INTERPRETER



In this instance of star name and designation disagreeing, the observer meant to record chi Cyg, but the handwritten Greek letter chi (χ) was read as "X" by the data entry technician.

Solution: Always write out the Greek letter names. (eg. beta Per rather than β Per)

Chapter 13: Variable Stars and O–C Diagrams

Summary

If a phenomenon is perfectly regular, then it is possible to predict its future behavior. If the period of a variable star is known and it is periodic, then the times of maxima and minima can be predicted. If the predictions and the future observations are plotted on an O–C (O minus C) diagram, any changes in the period can be detected. The O–C diagram is a sophisticated diagnostic tool to analyze periodicity.

Terminology

accretion disk	mode switching	secondary
composite-spectrum binary	O–C diagram	semi-detached binary
conjunction	primary	tertiary
ephemeris, ephemerides	Roche lobe	very long baseline interferometry

SUGGESTIONS FOR THE POSTER PAGES, INVESTIGATIONS, AND ACTIVITIES

Investigation 13.1: Constructing an *O–C* Diagram

Your students need some type of a timing activity to collect data to construct an *O–C* diagram. The timing needs to be something long enough to count and short enough to handle. The student pages suggests timing a street light when it changes for a certain period of time, or timing the breaks between commercials during a television program. If you are in a physics lab and want this to be a classroom activity you can use an object mounted on a slowly turning bicycle wheel or a torsion pendulum. Whether it is a homework activity or a classroom activity, the students need to have observed ten cycles or occurrences of their system. You may have students determine their own systems, have the entire class use the same system, or have groups do different systems.

Core Activity 13.2: Understanding *O–C* with Miras

Answer key:

SU Vir—The period is longer than average until about cycle 70. Then, there is a *single* short cycle, which causes an effective shift of *epoch*. The period is still slightly longer than average up to about cycle 112, then the period shortens until about cycle 120. It goes back to average until about cycle 137, then the period shortens.

X Aur—The period is about average until about cycle 45. Then it shortens considerably, until about cycle 60. Then there is a long stretch of longer-than-average period, until about cycle 110, followed by a long stretch of shorter-than-average period until about cycle 190.

Y Per—The period is shorter than average until cycle 30 or so, longer than average until about cycle 100, then shorter again. Note that a single short cycle around cycle 121 causes a large shift in epoch.

Z Aur—The period is very stable, and shorter than average, until about cycle 122. Then the period lengthens. Z Aur is the most clear-cut example of a sudden period change.

RU And - The period is longer than average until about cycle 35, then shorter than average until about cycle 72. The period shows large fluctuations until about cycle 90, then a longer-than-average period up to the present.

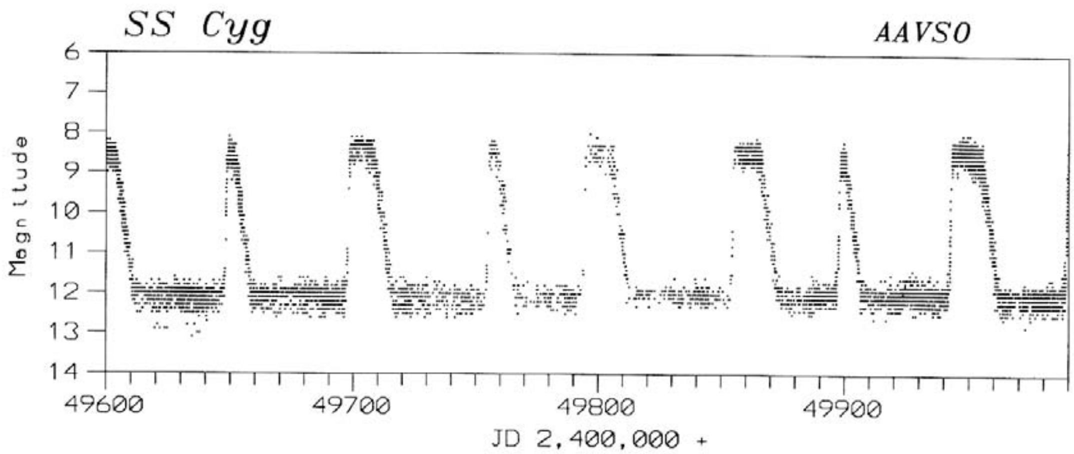
SS Cas—The period is first longer (about cycles 70-90), then shorter (cycles 90-120), then longer (cycles 120-170), then shorter (cycles 170-220.)

X Cam—The period is shorter than average until about cycle 50. Then it is slightly longer than average until about cycle 130. Finally, the period is about average from about cycles 150 to 220.

T Phe—There is no apparent change in the period, except for fluctuations from one cycle to the next; those fluctuations appear to be random.

Core Activity 13.3: Prediction of SS Cyg

SS Cyg is an eruptive variable and it is not possible to accurately predict future eruptions. Show your students the second diagram below to compare with their results.



Activity 13.4: Prediction and Observation of Delta Cep

If there are classroom observations for delta Cep or any other variable star, have the class predict future maxima at an appropriate time for actual observations. Writing a calculator or computer program to calculate the times is the most efficient. Have the class observe the star at some of the appropriate times. They will have to watch for more than the time of predicted maxima in order to determine when the observed times of maxima actually occur. An analysis of the *O–C* diagram should show that delta Cep is not changing its period and the data will cluster around 0 on their graph. If they have the wrong epoch, the points will cluster around a horizontal line that is not located at 0.

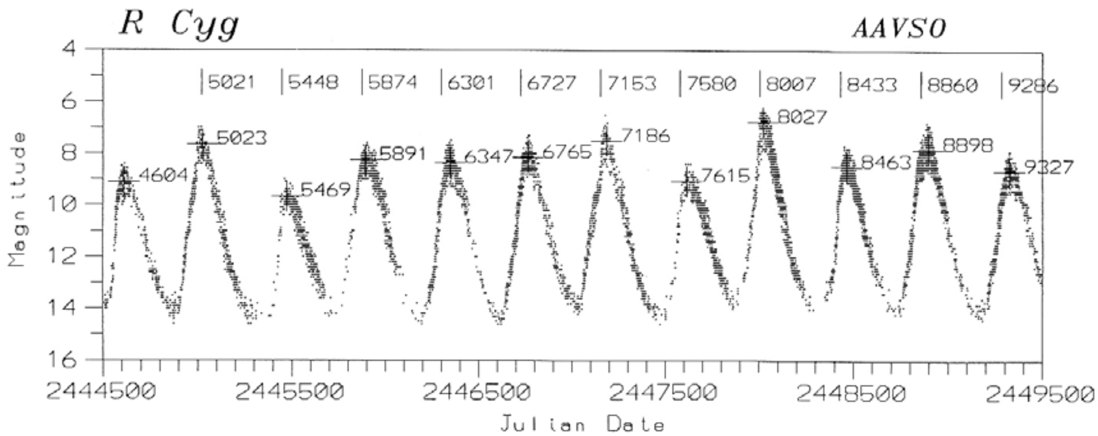
Poster Page: Universal Models

No part of astronomy is more fascinating to young people than that of the shape and structure of spacetime and space travel. Sadly, this subject is rarely included in science curricula. "Modern physics," including quantum mechanics and Einstein's theories of general and special relativity, have been around since the beginning of the 20th century!

Though cosmological models involve rigorous mathematics, the basic ideas of relativity and quantum mechanics can be grasped by students at all levels of ability. One short and easy-to-read book, ***Flatland,*** by Edwin S. Abbott (ISBN 048627263x), is an excellent introduction to the idea of dimensionality, as well as containing a wealth of social and historical science issues for research projects and extensions into literature and history classes. An excellent book for understanding motion at the quantum level is ***Alice in Quantumland,*** by Robert Gilmore (ISBN 0387914951), a take-off of Lewis Carroll's *Alice in Wonderland.*

Core Activity 13.5: Prediction and Analysis of the Period of R Cyg

After the students have determined the times and maximum brightness for R Cyg by fitting a polynomial with the V STAR program, show them the following chart with the predicted values. The students can construct an *O–C* diagram using their results from the observational data and the predictions to determine if the behavior of R Cyg is changing. Students may notice that the interval between consecutive maxima and their brightnesses is related in the following way: the fainter the maximum, the longer the interval from the previous maximum, and vice versa.



Activity 13.6: *O–C* Diagram for Eclipsing Binary Stars

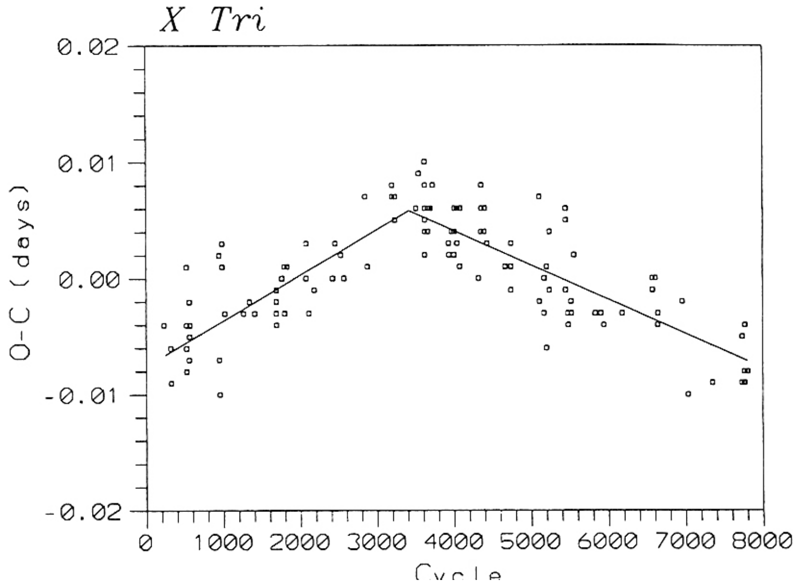
Answer Key

Correct results for minima of X Tri:

Cycle	JD(observed)	JD(computed)	O–C
230	2442726.175	2442726.179	-0.004
318	2442811.668	2442811.674	-0.006
322	2442815.551	2442815.560	-0.009
523	2443010.832	2443010.838	-0.006
524	2443011.802	2443011.810	-0.008
524	2443011.806	2443011.810	-0.004
524	2443011.811	2443011.810	0.001
557	2443043.863	2443043.870	-0.007
560	2443046.783	2443046.785	-0.002
564	2443050.666	2443050.671	-0.005
567	2443053.582	2443053.586	-0.004
945	2443420.818	2443420.825	-0.007
948	2443423.741	2443423.739	0.002
952	2443427.615	2443427.625	-0.010
984	2443458.717	2443458.714	0.003
985	2443459.687	2443459.686	0.001
985	2443459.689	2443459.686	0.003
1020	2443493.687	2443493.690	-0.003
1021	2443494.658	2443494.661	-0.003
1262	2443728.797	2443728.800	-0.003
1338	2443802.635	2443802.637	-0.002
1408	2443870.641	2443870.644	-0.003
1686	2444140.727	2444140.730	-0.003
1687	2444141.700	2444141.701	-0.001
1688	2444142.671	2444142.673	-0.002
1689	2444143.641	2444143.645	-0.004
1760	2444212.623	2444212.623	0.000
1762	2444214.566	2444214.566	0.000
1795	2444246.628	2444246.627	0.001
1797	2444248.567	2444248.570	-0.003
1829	2444279.660	2444279.659	0.001
2075	2444518.656	2444518.656	0.000
2077	2444520.602	2444520.599	0.003
2112	2444554.600	2444554.603	-0.003
2182	2444622.609	2444622.610	-0.001
2419	2444852.863	2444852.863	0.000
2452	2444884.926	2444884.923	0.003
2527	2444957.790	2444957.788	0.002
2566	2444995.678	2444995.678	0.000
2845	2445266.743	2445266.736	0.007
2878	2445298.797	2445298.796	0.001
3197	2445608.722	2445608.715	0.007
3198	2445609.694	2445609.686	0.008
3233	2445643.695	2445643.690	0.005
3233	2445643.697	2445643.690	0.007
3508	2445910.867	2445910.861	0.006
3544	2445945.845	2445945.836	0.009
3619	2446018.711	2446018.701	0.010
3621	2446020.646	2446020.644	0.002
3621	2446020.649	2446020.644	0.005
3621	2446020.652	2446020.644	0.008
3622	2446021.618	2446021.616	0.002
3622	2446021.618	2446021.616	0.002
3622	2446021.618	2446021.616	0.002
3622	2446021.620	2446021.616	0.004

3626	2446025.508	2446025.502	0.006
3659	2446057.567	2446057.563	0.004
3660	2446058.540	2446058.534	0.006
3690	2446087.686	2446087.680	0.006
3725	2446121.692	2446121.684	0.008
3934	2446324.737	2446324.734	0.003
3936	2446326.679	2446326.677	0.002
3974	2446363.599	2446363.595	0.004
4003	2446391.772	2446391.770	0.002
4004	2446392.745	2446392.741	0.004
4008	2446396.633	2446396.627	0.006
4042	2446429.665	2446429.659	0.006
4044	2446431.605	2446431.602	0.003
4078	2446464.635	2446464.634	0.001
4079	2446465.612	2446465.606	0.006
4322	2446701.688	2446701.688	0.000
4354	2446732.781	2446732.777	0.004
4356	2446734.726	2446734.720	0.006
4358	2446736.671	2446736.663	0.008
4389	2446766.785	2446766.781	0.004
4391	2446768.728	2446768.724	0.004
4397	2446774.559	2446774.553	0.006
4432	2446808.560	2446808.557	0.003
4668	2447037.839	2447037.838	0.001
4740	2447107.788	2447107.789	-0.001
4741	2447108.761	2447108.760	0.001
4742	2447109.735	2447109.732	0.003
4742	2447109.735	2447109.732	0.003
5107	2447464.348	2447464.341	0.007
5108	2447465.310	2447465.312	-0.002
5168	2447523.601	2447523.604	-0.003
5169	2447524.576	2447524.576	0.000
5200	2447554.687	2447554.693	-0.006
5202	2447556.637	2447556.636	0.001
5237	2447590.644	2447590.640	0.004
5238	2447591.611	2447591.612	-0.001
5446	2447793.689	2447793.690	-0.001
5447	2447794.661	2447794.662	-0.001
5447	2447794.667	2447794.662	0.005
5448	2447795.639	2447795.633	0.006
5449	2447796.604	2447796.605	-0.001
5477	2447823.805	2447823.808	-0.003
5478	2447824.776	2447824.779	-0.003
5481	2447827.690	2447827.694	-0.004
5516	2447861.695	2447861.697	-0.002
5520	2447865.581	2447865.584	-0.003
5555	2447899.589	2447899.587	0.002
5829	2448165.784	2448165.787	-0.003
5903	2448237.677	2448237.680	-0.003
5903	2448237.677	2448237.680	-0.003
5942	2448275.566	2448275.570	-0.004
6180	2448506.792	2448506.795	-0.003
6570	2448885.692	2448885.692	0.000
6573	2448888.606	2448888.607	-0.001
6608	2448922.610	2448922.610	0.000
6637	2448950.781	2448950.785	-0.004
6639	2448952.724	2448952.728	-0.004
6641	2448954.668	2448954.671	-0.003
6642	2448955.638	2448955.642	-0.004
6957	2449261.673	2449261.675	-0.002
7031	2449333.558	2449333.568	-0.010
7348	2449641.535	2449641.544	-0.009
7728	2450010.717	2450010.726	-0.009
7734	2450016.550	2450016.555	-0.005
7763	2450044.721	2450044.730	-0.009
7764	2450045.693	2450045.701	-0.008
7769	2450050.555	2450050.559	-0.004
7800	2450080.669	2450080.677	-0.008

The O–C values for X Tri gradually increase until about cycle 3400; thereafter they gradually decrease. The general trend is shown by the two straight line segments in the following graph.



Each straight line represents a different period, so we see two different periods of X Tri. Up to cycle 3400, the slope of the line is positive, so the actual period is slightly longer than the given period. After cycle 3400, the slope of the line is negative, so the actual period is slightly shorter than the given period.

In summary: X Tri shows a period change, from a period slightly longer than the given period, to a period slightly shorter.

Poster Talk: The Birch Street Irregulars

This humorous poster talk addresses the serious topic of the need for variable star observers to be careful and precise when recording and reporting observational data. "The Birch Street Irregulars" is also an excellent example of the lengths to which the staff of supporting scientific organizations such as the AAVSO will go to ensure that the data disseminated to the scientific community are as error-free as possible.

Glossary

AAVSO — The American Association of Variable Star Observers, located in Cambridge, Massachusetts, is an astronomical organization specializing in variable stars. It maintains the largest variable star database in the world.

absolute error —See **percentage error**.

absolute magnitude — The apparent brightness of a star computed as if placed at a standard distance of 10 parsecs from the Earth. See also **luminosity**.

absorption lines — Dark lines which appear in a continuous spectrum where light with specific wavelengths has been removed, or absorbed.

accretion disk — Material from the atmosphere of a star which spirals around the surface of a more dense companion in a binary star system, forming a disk.

accuracy — How closely a measurement agrees with the true or accepted value of the quantity being measured.

actual brightness —The absolute magnitude of a star (see above).

alias, aliases — A false period which seems to be significant in a period search.

amplitude — The difference between the maximum and minimum brightness in a light curve.

antisolar point — A straight line from the Sun, through an observer's eyes, to the center point, or radius, of the arc of a rainbow.

apogee — The point in the Moon's orbit at which it is at its greatest distance from Earth.

apparent brightness — The brightness that a star appears to have for an observer on Earth; same as apparent magnitude.

apparent magnitude —The brightness that a star appears to have for an observer on Earth.

apsidal motion — The rotation of the major axis of the elliptical orbit of stars in a binary star system, such that there is a gradual shift of the point where the two stars reach their closest approach to each other.

asterism — The most prominent pattern of stars within a constellation; e.g., the Big Dipper is the asterism for the constellation Ursa Major.

asteroid belt — The region between the planets Mars and Jupiter where the majority of asteroids are located.

asteroids — Chunks of rocky debris (sometimes called "minor planets") which are mostly contained within the asteroid belt.

astrometry — The branch of astronomy which measures the positions of celestial bodies in right ascension and declination coordinates.

astronomical unit — The value of one astronomical unit (AU) is the distance between the Earth and the Sun.

average deviation — A mathematical method of assessing the spread, or range, of a set of values or of a data set.

azimuth — A coordinate system to measure angular distances along the horizon, with North as the zero point.

Balmer series — Hydrogen emission and absorption lines that fall in the visible part of the spectrum.

barycenter — The common center of mass around which two gravitationally-bound objects orbit.

bell curve — See **normal curve**.

bin, bin value — A subset of values, useful in determining the frequency with which a particular value appears within a set of values.

binary system — A system of two or more gravitationally-associated stars in orbit around their barycenter.

black body — A hypothetical ideal radiator which absorbs all radiation without reflecting or transmitting any of it, and then radiates it all away.

black body radiation — The continuous distribution of wavelengths of thermal radiation emitted from a black body at a particular temperature.

black dwarf — The cold carbon core left after a white dwarf radiates all of its energy into space.

black hole — The end product of the death of the most massive stars, leaving a region of space so gravitationally compact that light cannot escape.

bright line spectrum — See **emission spectrum**.

brown dwarf — A dim object about 80 times more massive than Jupiter, but not massive enough for continuous fusion to occur within its core.

cataclysmic variable — A binary system consisting of a Sun-like or larger star and a white dwarf. Matter from the larger star accretes onto a disk surrounding the gravitationally-stronger white dwarf. Instabilities in the accretion disk cause eruptions, which appear as visible brightenings to observers on Earth. See also **accretion disk**, and **eruptive variable**.

celestial sphere — An imaginary transparent hollow sphere centered on the Earth with Earth's coordinate system of longitude and latitude extended outward and superimposed onto the sphere (right ascension and declination, respectively).

Cepheid variable — A pulsating variable star with a period from 1 to 70 days, and an amplitude of light variation from 0.1 to 2.0 magnitudes. Cepheids have high luminosity, and are of F spectral class at maximum and G to K at minimum. Cepheids obey the period-luminosity relationship

clusters — Groups of galaxies which are gravitationally associated. The Milky Way Galaxy is one of ~24 galaxies which belong to the Local Group cluster.

comets — Small bodies of ice and dust travelling in an elliptical orbit about the Sun. As they near the Sun, they begin to vaporize, thus forming extended tails of ions and dust.

comparison stars — Stars of known magnitude which are used to estimate the varying brightness of a nearby variable star.

composite-spectrum binary — A system of two stars so close together that their individual features can be revealed only by spectroscopic analysis. Also called spectroscopic binary.

conjunction — The alignment of two or more celestial bodies in the Solar System so that they have the same longitude as seen from the Earth.

constellation — Organized patterns of stars in the night sky.

continuous spectrum — A spectrum in which the electromagnetic radiation is distributed over all frequencies.

convective zone — The zone beneath the photosphere of the Sun where convection currents transport the energy produced by nuclear fusion towards the surface.

cosmology — The study of the origin, evolution, large-scale structure, and possible futures of the universe.

cycle — The time interval required for a particular behavior to be completed once.

declination — The extension of the coordinate of latitude on Earth to the celestial sphere. It is measured in degrees, the same as latitude on Earth.

dispersion — The separation of a beam of light into its component colors, i.e., component wavelengths, so that a spectrum is formed.

distance modulus — A mathematical relationship among the absolute magnitude, apparent magnitude, and distance of a star.

double blind — An experiment in which neither the test subject nor the scientist recording data knows which experiment is being performed on that test subject.

dwarf nova — A cataclysmic variable that has eruptions at intervals of 10 to several hundreds of days, resulting in light increases of 2 to 6 magnitudes.

eclipsing binary — Binary system of stars with an orbital plane lying near the line of sight of an observer on Earth. The components periodically eclipse each other, causing a decrease in the apparent brightness of the system as seen by the observer. The period of the eclipse, which coincides with the orbital period of the system, can range from minutes to years.

ecliptic — The apparent path of the Sun. It is represented on the celestial sphere as a dotted line which extends 23½° into the northern hemisphere and 23½° into the southern hemisphere. It is a reflection of the 23½° tilt of the Earth's axis.

effective temperature — The surface temperature of a star, expressed as the temperature of a black body having the same radius as the star and radiating the same total amount of energy per unit area per second.

electromagnetic radiation (electromagnetic spectrum) — The entire spectrum of radiation from radio waves to gamma rays, which consists of alternating electric and magnetic energy fields that transfer energy and information without a medium.

electron degeneracy pressure — The repulsive force between electrons which keeps white dwarfs in equilibrium and prevents further gravitational collapse.

emission lines — Bright lines in specific locations of the spectra of radiating materials, corresponding to the emission of light at specific wavelengths and frequencies.

emission spectrum — The pattern of spectral lines produced by an element.

envelope — A band on a graph which encloses the error bars and represents 68% of the graphed data.

ephemeris (plural: **ephemerides) —** A list of predicted positions of the Sun, Moon, and planets, as well as information relating to times of maxima or minima of variable stars.

epoch — A precise instant that can be used as a fixed reference point of time, such as a time of maximum magnitude for a variable star.

error bar — A line drawn on a graph to represent the range of error for a data point.

eruptive variable — A star whose variability is caused by eruptions in the star or stellar system, i.e., supernovae, novae, recurrent novae, dwarf novae, and symbiotic stars. See **cataclysmic variable**.

extrapolation — The process of inferring unknown information from known information.

extrinsic variable — A star whose variability is caused either by the eclipse of one star by another or by the effects of stellar rotation of bright or dark patches (flares, starspots).

false-alarm probability — The probability that a result is obtained which appears to be significant, but actually only happened by accident (“random fluctuation”).

finder charts — Star maps used to locate fields of variable stars.

folded light curve — A plot of magnitude as a function of phase, rather than as a function of time. For a periodic light curve, this allows successive cycles to be “folded” on top of each other. See also **phase diagram**.

galaxy — A gravitationally-bound conglomerate of stars, dust, and gas.

***General Catalogue of Variable Stars* (GCVS) —** A catalogue which lists the relevant information pertaining to all known variable stars.

general relativity — A theory of gravitation which concludes that gravitational fields change the geometry of spacetime, causing it to become curved. The curvature of spacetime controls the natural motions of bodies. Matter affects how spacetime curves, and spacetime affects how matter moves.

globular cluster — Tightly-bound spherical groups of hundreds of thousands of stars which reside in galactic halos.

gnomon [“ˈnō mon”] — A vertical shaft whose shadow is used to measure the altitude of the Sun to determine the time of day, and the day of the year.

Greenwich Mean Astronomical Time (GMAT) A time-keeping system used by astronomers, in which each day begins at 12 noon in Greenwich [“ˈgren ich”], England (at 0° longitude).

ground state — The first orbital level, or lowest energy state, of an electron in orbit around an atomic nucleus.

H-R diagram (Hertzsprung-Russell diagram) — A stellar plot of luminosity or absolute magnitude versus temperature or spectral class, illustrating stellar evolution.

heliacal rising — The rising of a celestial object just before the Sun; such an object is visible only in the early morning.

helium flash — The explosive onset of helium burning in the core of a star.

highlands — The light-colored terrain on the lunar surface, more highly elevated than the maria and containing older materials.

HIPPARCOS — The European Space Agency's HIgh Precision PARallax COllecting Satellite, which measured the distances to stars within 500 light-years of the Sun with a precision in the milliarcsecond range.

histogram — A bar graph of relative frequency versus bin value.

horizon —The point at which the sky meets the Earth for an observer.

horizon window — An elliptical opening on a planisphere through which a star chart is viewed.

Hubble's constant — The constant of proportionality in Hubble's law relating the recessional velocity of a galaxy to its distance.

Hubble's Law — The recessional velocity and distance of a galaxy are directly proportional to each other, i.e., the farther away a galaxy, the greater its velocity of recession.

hydrostatic equilibrium — The force of gravity pulling inward on a star, balanced by the radiation pressure pushing outward.

interpolation — Estimating a numerical value between two measured values, such as estimating the magnitude of a variable star using the known magnitudes of a fainter and a brighter comparison star.

interstellar medium — The matter (mainly gas and dust) occupying the space between stars.

intrinsic variable — A star which varies in magnitude due to internal physical changes which result in pulsations or eruptions.

inverse square law — A relationship displayed by any phenomenon which radiates outwards in all directions from a source and decreases as the square of the distance from the radiating source, e.g., radiation and gravity.

Julian Date — The Julian Day (see below) plus the fractional part of the day that has elapsed since the preceding noon.

Julian Day — A unit of time equal to the number of days that have elapsed since noon Greenwich Mean Time on January 1, 4713 BC.

Kelvin — A temperature scale based on absolute zero, where all molecular motion ceases; equal to –273° C.

Kuiper belt — A region in the plane of the Solar System outside the orbit of Neptune where most short-period comets are thought to originate.

libration — The rocking motions of the Moon, both apparent and real, that allow Earth observers to see 59% of the lunar surface.

light curve — A plot of variation in magnitude versus time for a variable star.

light pollution — The contamination of the night sky due to excess artificial lighting.

light-year —The distance that light travels in one year, i.e., ~9,670,000,000 km.

limb — The apparent edge of any celestial body with a detectable disc.

line of apsides — The longest axis of an elliptical orbit.

local mean time — The time for a specific location in any one of the 24 internationally-recognized time zones into which the Earth is divided.

long-period variable — See **Mira variable**.

luminosity — The intrinsic or absolute brightness of a star, equal to the total energy radiated per second from the star, i.e., the total outflow of power.

Lyman series — Hydrogen spectral lines in the far ultraviolet region produced by electron transitions from higher "allowed orbits" to the ground state.

magnitude — A measure of the brightness of a star. The brighter a star, the lower the value of its magnitude.

main sequence — The band on the H-R diagram containing the ~90% of all stars which have stable thermonuclear fusion ongoing in their cores.

maria — Dark patches on the lunar surface resulting from basaltic lava flows three to four billion years ago.

maximum (plural: **maxima) —** The brightest magnitude(s) of a variable star.

meridian — An imaginary line running from North to South, passing directly overhead for an observer.

meteorites — Chunks of rocky interplanetary debris large enough or hard enough to survive entry through Earth's atmosphere and land on the surface.

meteoroids — Chunks of rocky interplanetary debris outside the Earth's atmosphere.

meteors — Bright streaks in the sky referred to as "shooting stars" which are small pieces of interplanetary rocky debris encountering Earth's atmosphere.

meteor showers — An event during which many meteors can be seen each hour, caused by the yearly passage of the Earth through the debris left behind in the orbits of comets.

microwave band — The band of radiation that lies between radio and infrared.

Milky Way — The band of stars across the sky which is actually the disk of our home galaxy (the Milky Way Galaxy), and which contains most of the stars, gas, and dust of our galaxy.

minimum (plural: **minima) —** The dimmest magnitude(s) of a variable star.

minor planets — Another name for asteroids.

Mira — The first Mira-type variable star discovered; also called omicron Ceti.

Mira variable — A red giant with a long period ranging from 80 to 1000 days and visual light amplitude ranging from 2.5 to 5 magnitudes or more.

mode switching — The switching from one period to another by a pulsating variable star.

modular arithmetic — Arithmetic in which the integer part of all numbers is ignored. If applied consistently to quantities for which the integer part is unimportant, this is a mathematically sound method.

momentum — The tendency of a moving object to continue moving.

moon — A natural body which orbits a planet.

nebulae — Clouds of gas within the Milky Way which absorb, radiate, or reflect radiation.

nebulosity — A cloud of gas and dust surrounding a symbiotic star.

neutron degeneracy pressure — The repulsive force between neutrons; i.e., the strong nuclear force which keeps a neutron star from further gravitational collapse.

neutron star — The dense core of neutrons left behind after a massive star has gone through a supernova explosion.

normal curve — A symmetrical bell-shaped curve representing a normal distribution of a data set.

normal distribution — The most common probability distribution in nature, also referred to as the "bell curve" because of the shape of its graph. A probability distribution gives the chance of getting any particular result.

nova (plural: **novae) —** A white dwarf star in a close binary system that suddenly increases in brightness when material accumulating on its surface from its companion star causes thermonuclear reactions.

***O–C* diagram —** A graph of the difference between the observed and calculated times of maxima or minima versus the epoch.

Oort Cloud — A spherical halo of icy material which surrounds the Solar System at a distance of ~50,000 AU, and from which long-period comets originate.

optical double — A pair of stars that appear close together in the sky only because they happen to lie in very nearly the same direction from Earth.

oscillator — An object which undergoes periodic vibrational motion.

parallax — The apparent motion of a relatively close object with respect to a more distant background as the location of the observer changes.

percentage error — The difference between an observed value and the true or accepted value.

periastron — The point in any orbit around a star that is nearest to the star, or the closest approach of the two components of a binary star system.

perigee —The point in the orbit of the Moon or a satellite at which it is at its closest approach to Earth.

perihelion — The point in the orbit of a planet or other body at which it is at its closest approach to the Sun.

period — The length of time for one complete cycle of a variable star, i.e., the time between successive maxima or minima.

periodic — The regular repetition of cyclic behavior.

period-luminosity relationship — A relationship between the periodicity and absolute magnitude of a Cepheid variable star.

Perseid —A meteor shower in mid-August which seems to radiate from the constellation Perseus.

phase — A periodic phenomenon whose variation depends only on where it is in its cycle (because all cycles are identical).

phase diagram — A graph that plots magnitude versus cycles which fold over themselves repeatedly. See also **folded light curve**.

photoelectric photometry — The precise measurement of light using a photoelectric photometer.

photometer — An instrument which measures the intensity of light from a radiating source, such as a star or galaxy.

photometry — A branch of observational astronomy which studies the light intensity of stars and galaxies.

photons — Bundles of electromagnetic energy which make up the electromagnetic spectrum.

photosphere — The visible "surface" of the Sun lying at the bottom of the Sun's atmospheric layers and on top of the convective zone of the Sun's interior.

Planck's law — Describes the continuous spectrum of a black body, i.e., a hotter black body will emit more of every wavelength of radiation than a cooler black body. The frequency at which the emitted intensity is highest is an indication of the temperature of the radiating object.

planet — A body in orbit around a star which shines by reflected light from the star.

planetary nebula — The ejected atmospheric material from a red giant star on its way to becoming a white dwarf.

planetary system — A star and its family of orbiting planets.

planetoids — Small rocky objects in orbit around the Sun; often referred to as minor planets; include asteroids.

planisphere — An astronomical observing tool used to determine which constellations are in the sky for any date and time of the year.

Pogson's method of bisected chords — A graphical method of determining the maxima and minima on a light curve of a variable star.

Polaris — The handle star of the Little Dipper in Ursa Minor, which is at this time the closest star above the terrestrial North pole; the North Star.

precession — The slow change in the direction of the rotational axis of a spinning object caused by some external force such as gravity.

precision — The degree of refinement with which an operation is performed or a measurement is stated.

primary — The brighter star in an eclipsing binary star system, the eclipsing of which by its dimmer companion produces the deeper minimum from the perspective of an observer on Earth.

probability — A mathematical basis for predicting an outcome.

pulsar — A rapidly rotating neutron star whose magnetic field causes beams of radiation to sweep outward as the star spins.

pulsating variable — A star which expands and contracts with a regular or fairly regular period due to physical changes within the star.

quadrant — An astronomical device used to measure the altitude of celestial objects.

R Coronae Borealis star — Luminous, oxygen-poor, carbon-rich, and rare variable which spends most of its time at maximum, and at irregular intervals fades by as many as nine magnitudes.

radiation pressure — The pressure exerted on a surface by light or other electromagnetic radiation. The radiation is in the form of photons and the pressure is the result of a transfer of momentum from the photons to the surface.

radiative zone — The region of a star's interior surrounding the core where energy in the form of photons is carried towards the surface.

random error — Inconsistencies in measurement which decrease in proportion to the square root of the number of measurements.

range — The difference between the smallest and largest values in a set of data.

recessional velocity — The velocity with which distant galaxies are receding from Earth, as measured by redshifts in their spectra.

recurrent nova — A close binary system with a Sun-like star and a white dwarf component which has had more than one nova outburst during its recorded history.

red dwarf — Small, cool, faint stars in the lower right corner of the main sequence in the H-R diagram.

red giant — A dying star with bright absolute magnitude and a relatively low surface temperature. Such stars glow with a reddish color.

reflection — A property that light exhibits when it hits a surface between two different media and the light (wavelength) is redirected back into the medium it was leaving.

refraction — A property that light exhibits when it leaves one medium and enters another, being redirected or "bent" due to the differing densities of the two media.

relative frequency — The fraction of all the data which falls within a certain range of values.

revolution — The orbit of a body around a gravitational center. The Earth revolves around the Sun in one Earth year, ~365¼ days.

right ascension — The Earth equivalent of longitude extended out to the celestial sphere and measured in hours, minutes, and seconds of time.

Roche Lobe — The tear-shaped volume of space surrounding a star in a binary system in which the star's gravity is strong enough to hold onto its loose atmospheric material.

rotating variable — A rapidly rotating star, usually in a binary system, which undergoes small-amplitude changes in light due to starspots (i.e., sunspots) on its surface.

rotation — The spinning of a body around a central axis. The Earth completes one rotation on its axis every 24 hours.

RV Tauri star — Yellow supergiant pulsating star with characteristic light variation composed of alternating deep and shallow minima.

satellite — A natural object in orbit around a planet, such as a moon, or a human-built object in orbit around a planet, moon, or other celestial body.

secondary — The dimmer of two stars in a binary star system, the eclipsing of which by its brighter companion produces a shallow dip (secondary minimum) in light variation from the perspective of an observer on Earth.

semidetached binary — A binary system in which one component has filled its Roche Lobe and is transferring material to its companion.

semiregular variable — A star which shows appreciable periodicity accompanied by intervals of irregular light variation.

sensitive — A statistical estimate or test is called sensitive if it has a very small likely error, or is very good at detecting what it is looking for.

sidereal ["sīˈdir ēəl"**] time —** Telling time by the passage of stars on the celestial sphere (right ascension) across an observer's meridian.

sidereal day — A unit of time approximately 24 hours in length (measured from midnight to midnight) when the vernal equinox at 0^h Right Ascension passes over the observer's meridian.

significant digits —The number of digits in a numerical value which are reasonably certain.

singularity — A point of infinite density and zero radius, i.e., a black hole.

***Sky-Gazer's Almanac* (SGA) —**
An astronomical tool for observers which gives the times when planets are visible and when objects transit the meridian, the times of sunrise and sunset, and the times of lunar risings, settings, and phases.

skyglow — The contamination of dark skies by light pollution, especially near metropolitan areas.

Solar System — The Sun and its planets (Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, Pluto), asteroids, and other objects that orbit the Sun.

solstice — The point at which the Sun is at its farthest ascent into the northern hemisphere (summer solstice), or its farthest descent into the southern hemisphere (winter solstice).

spectrophotometer — A tool which enables scientists to determine such information as chemical composition by analyzing the spectra produced by radiating objects, such as stars.

spectroscope — A device utilizing a prism or grating through which light is refracted, thereby producing a spectrum.

spectroscopy — The study of spectra.

spectrum — A display or record of the constituent wavelengths of electromagnetic radiation enabling scientists to analyze the wavelengths and their intensities.

spiral galaxy — A galaxy composed of a flattened disk component with spiral arms and a large central galactic bulge.

standard deviation — The square root of the variance, which gives a very good measure of the size of a "typical" error in a single observation.

standard error of the average — The standard deviation of the data, divided by the square root of the number of data points going into that average.

standstill — An interval of constant brightness of unpredictable duration, but which can last the equivalent of several cycles, in Z Camelopardalis-type eruptive variables. Also called "stillstand."

star — A luminous sphere of gas which radiates its own energy due to the thermonuclear fusion process in its core.

star chart — A map of a particular region of the sky showing the relative positions of stars and other celestial objects.

statistics — The branch of mathematics concerned with organizing and analyzing numerical data for the purposes of description and prediction. It is especially concerned with the analysis of errors and random phenomena.

Stefan-Boltzmann's Law — A relationship determining the total energy emitted over all wavelengths per second per unit area of a black body; i.e., the total power output of a black body (star).

stellar evolution — The changes that stars undergo from birth through death.

SU Ursae Majoris star — A close binary system that undergoes eruptions, with two distinct types of outbursts: one is faint, frequent, and of short duration, and the other is bright, less frequent, and of longer duration.

subharmonics — A period which is an exact multiple of the real period of a variable star.

supercluster — A collection of clusters of galaxies that are gravitationally bound. The Milky Way Galaxy belongs to the cluster known as the Local Group, which is one of the clusters belonging to the Virgo supercluster.

supergiant — A star with a radius between 100 and 1000 times the radius of the Sun.

superhumps — Small periodic modulations that occur during the superoutbursts of SU Ursae Majoris-type eruptive variables.

supernova (plural: **supernovae) —** The catastrophic explosion which ends the life of a massive star, leaving a black hole or neutron star behind.

superoutburst — The bright, less frequent, and longer-lasting outburst associated with SU Ursae Majoris-type eruptive variables.

symbiotic star — A close binary system with one component a red giant and the other a hot blue star embedded in nebulosity; a type of eruptive variable.

synchronous rotation — When the period of rotation is equal to the average orbital period, such that only one face is seen, as with the Moon.

systematic error — Inherent errors which are relatively constant and never cancel out (unlike random errors).

T Tauri star — Young, pre-main sequence star in the process of birth, which does not as yet have stable thermonuclear processes in its core.

terminator — The line dividing the dark and sunlit areas of the Moon (or other celestial objects illuminated by the Sun).

tertiary — A star which orbits the two main components of a binary star system.

transit — The daily passage of a celestial body across an observer's meridian through the point closest to the observer's zenith.

trend — A line on a graph which represents the general behavior of the total accumulation of a data set.

U Geminorum star — Dwarf nova-type cataclysmic variable which erupts at intervals of 30 to thousands of days. Between eruptions it has distinct periods of quiescence. Also called SS Cygni-type dwarf nova.

variable star — A star that displays variations in brightness due to intrinsic or extrinsic factors.

variance — The square of the standard deviation.

very long baseline interferometry (VLBI) — Radio observations of the same extraterrestrial source made with widely separated radio telescopes.

wave-particle duality — The nature of light: when traveling, light exhibits the properties of waves, and when interacting with a surface, light exhibits the properties of particles.

wavelength — The distance over which a periodic wave motion goes through one complete cycle of oscillation.

white dwarf — The end product of a collapsed average-mass star (such as the Sun), held in equilibrium by electron degeneracy pressure and gravity.

Wien's law — As temperature increases for black body radiation, the maximum wavelength output moves to shorter wavelengths.

Z Camelopardalis star — A type of dwarf nova whose cyclic light variations are interrupted by intervals of constant brightness. See also **standstill**.

zenith — The point on an observer's meridian which is directly overhead.