SCI 238 — Introduction to Astronomy

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Contents

1 Chapter 1 – Our Place in the Universe **6**
1.1 Overview . . . 6
1.2 The Big Bang and the Expanding Universe . . . 6
1.3 The Birth of Stars . . . 6
1.4 Modelling the Universe . . . 7
1.4.1 Distance . . . 7
1.4.2 Time . . . 7
1.5 Motion of the Universe . . . 7
1.6 Dark Matter and Dark Energy . . . 8
1.7 Relative Galactic Movements . . . 8

2 Chapter 2 – Discovering the Universe **8**
2.1 The Motion of the Stars . . . 8
2.2 Constellations . . . 9
2.2.1 Variance . . . 9
2.3 Seasons . . . 10
2.3.1 Solstices . . . 10
2.4 Precession . . . 11
2.5 The Moon . . . 11
2.5.1 Eclipses . . . 12
2.6 Planets . . . 13

3 Chapter 3 – Ancient Astronomy **13**
3.1 Ancient Roots of Science . . . 13
3.2 Ancient Greek Science . . . 13
3.3 The Copernican Revolution . . . 14

4 Chapter 4 – Motion, Energy, and Gravity **14**

5 Chapter 5 – Light **17**

6 Chapter 6 – Formation of Planetary Solar Systems **21**
6.1 Overview . . . 21
6.2 Clues to the formation of the Solar System . . . 21
6.3 The Sun . . . 22
6.4 Mercury . . . 22
6.5 Venus . . . 22
6.6 Earth . . . 23
6.7 Mars . . . 23
6.8 Jupiter . . . 23
6.9 Saturn . . . 23
6.10 Uranus . . . 23
6.11 Neptune . . . 24
6.12 Pluto (and other dwarf planets) . . . 24
6.13 Where did the solar system come from? . . . 24
6.13.1 The Formation of the planets . . . 24
6.13.2 How do we explain the exceptions to rules? . . . 25
6.13.3 When did the Planet's form? . . . 25
6.13.4 Other Planetary Systems . . . 25
6.13.5 Comparing Extrasolar planets . . . 26

7 Chapter 10 – Our Star **26**
7.1 A Closer Look at the Sun . . . 26
7.1.1 History . . . 26
7.1.2 Nuclear Fusion . . . 27
7.1.3 Structure . . . 27
7.2 Nuclear Fusion in the Sun . . . 28
7.2.1 Proton-Proton Chain . . . 28
7.2.2 Solar Thermostat . . . 28
7.2.3 Path of Energy Through the Sun . . . 29
7.3 The Sun-Earth Connection . . . 30
7.3.1 Sunspots and Magnetic Fields . . . 30
7.3.2 Solar Storms . . . 30
7.3.3 Heating the Chromosphere and Corona . . . 30
7.3.4 Solar Cycles . . . 31

8 Chapter 11 – Surveying the Stars **31**
8.1 Properties of Stars . . . 31
8.1.1 Luminosity . . . 31
8.1.2 Temperature . . . 32
8.2 Mass . . . 32
8.3 Patterns Among Stars . . . 33
8.4 Main Sequence . . . 33
8.5 Giants, Supergiants, and White Dwarfs . . . 34
8.5.1 Giants and Supergiants . . . 34
8.5.2 White Dwarfs . . . 34
8.6 Star Clusters . . . 34
8.6.1 Types of clusters . . . 34

8.6.2 Age of a Cluster . . . 34

9 Chapter 13 – White Dwarfs, Neutron Stars, Black Holes 35
9.1 White Dwarfs . . . 35
9.1.1 What is a white dwarf? . . . 35
9.1.2 Composition, Density and Size . . . 35
9.1.3 The White Dwarf Limit . . . 35
9.1.4 White Dwarf in a binary System . . . 35
9.2 Neutron Stars . . . 36
9.2.1 What is a neutron star? . . . 36
9.2.2 How were they discovered? . . . 36
9.2.3 Neutron Star in a binary System . . . 36
9.3 Black Holes . . . 37
9.3.1 What is a Black Hole? . . . 37
9.3.2 Singularity and Limits of Knowledge . . . 37
9.3.3 Formation of a Black Hole . . . 37
9.3.4 Observational Evidence . . . 38
9.4 Origin of Gamma Ray Bursts . . . 38

10 Summary Notes 38

11 Chapter 14 38
11.1 Milky Way . . . 38
11.1.1 Appearance . . . 38
11.1.2 Stars in Orbit . . . 39
11.2 Galactic Recycling . . . 39
11.2.1 Gas Recycling . . . 39
11.3 Location of Star Formation . . . 40
11.4 History of the Milky Way . . . 41
11.5 Galactic Center . . . 41

12 Chapter 15 – Galaxies and the Foundation of Modern Cosmology 41
12.1 Types of Galaxies . . . 41
12.1.1 Spiral Galaxies . . . 42
12.1.2 Elliptical Galaxies . . . 42
12.1.3 Irregular Galaxies . . . 43
12.1.4 Hubble's Galaxy Classes . . . 43
12.2 Measuring Distance . . . 43
12.3 Age of the Universe . . . 45
12.3.1 Lookback Times . . . 45
12.4 Evolution of Galaxies . . . 46
12.4.1 Variances in Galaxies . . . 46
12.5 Quasars and Other Active Galactic Nuclei . . . 47
12.5.1 Quasars . . . 48
12.5.2 Power Source of Quasars and Active Galactic Nuclei . . . 48
12.5.3 Supermassive Black Holes . . . 48

13 Chapter 16 – Dark Matter, Dark Energy, and the Fate of the Universe **49**
13.1 Evidence . . . 49
13.2 Composition . . . 50
13.3 Dark Matter's Role . . . 51
13.4 The Fate of the Universe . . . 51
13.4.1 Expansion Patterns . . . 51

14 Chapter 17: The Beginning of Time **52**
14.1 The Big Bang . . . 52
14.1.1 Conditions of the Early Universe . . . 52
14.1.2 History of the Universe . . . 53
14.2 Evidence . . . 54
14.2.1 Left Over Radiation . . . 54
14.2.2 Abundance of Elements . . . 55
14.3 Inflation . . . 55
14.3.1 Mysteries . . . 55
14.3.2 Testing Inflation . . . 56
14.4 Observing the Big Bang . . . 56

15 Chapter 18 – Life in the Universe **57**

16 Assignments **58**
16.1 Assignment 1 . . . 58
16.2 Assignment 2 . . . 59
16.3 Assignment 3 . . . 59
16.4 Assignment 4 . . . 61
16.5 Assignment 5 . . . 61

17 Assignment 9 **63**
17.1 Assignment 11 . . . 65

18 Assignment 12 **68**
18.1 Dark matter . . . 68
18.2 Dark Energy . . . 69
18.3 Gravitational Lensing . . . 69
18.4 Eras of the Universe . . . 70
18.5 Cosmic microwave background . . . 70

19 Definitions **70**
19.1 Basic Astronomical Objects . . . 70
19.2 Collections of Astronomical Objects . . . 71
19.3 Astronomical Distance Units . . . 71
19.4 Terms Relating to Motion . . . 71
19.5 Telescopes . . . 72

20 Formulae and Values **72**

21 Data **73**

22 Lecture Slides **76**
22.1 Scale of the Universe . . . 76
22.1.1 Objects in the Universe . . . 76
22.1.2 Light Travels . . . 76
22.1.3 The Universe is Big . . . 76
22.1.4 Earth Moves Through Space . . . 77
22.2 Discovering the Universe for Yourself . . . 77
22.2.1 View from Earth . . . 77
22.2.2 Local Sky . . . 77
22.2.3 Measurements . . . 78
22.2.4 Star Rise . . . 78
22.2.5 Seasons . . . 78
22.2.6 The Moon . . . 79
22.2.7 Ancient Planets . . . 79
22.3 Science of Astronomy . . . 80
22.3.1 Ancient Greeks . . . 80
22.3.2 Copernican Revolution . . . 81
22.3.3 Scientific Theory . . . 82
22.3.4 Astrology . . . 83
22.4 Making Sense of the Universe: Understanding Motion, Energy, and Gravity . . . 83
22.5 Light and Matter: Reading Messages from the Cosmos . . . 84
22.5.1 Waves . . . 85
22.5.2 Matter . . . 85
22.5.3 Light . . . 85
22.5.4 Thermal Radiation . . . 85
22.5.5 Doppler effect . . . 86
22.6 Telescopes: Portals of Discovery . . . 86
22.7 Our Planetary System . . . 87
22.7.1 Spacecraft Exploration . . . 91
22.8 Other Planetary Systems: The New Science of Distant Worlds . . . 91
22.9 Life in the Universe . . . 92
22.9.1 Life on Other Planets . . . 94
22.9.2 Life Outside our Solar System . . . 95
22.9.3 Earth-like Planets . . . 95
22.9.4 The Search for Extraterrestrial Intelligence . . . 95
22.9.5 Interstellar Travel and Communications . . . 96
22.10 Space and Time . . . 96
22.10.1 Tests for Relativity . . . 97
22.11 Searching the Stars . . . 98
22.11.1 Brightness . . . 98
22.11.2 Star Spectrums . . . 98
22.11.3 Thermal Radiation . . . 98
22.11.4 Binary Systems . . . 98
22.12 Patterns Among Stars . . . 99
22.13 Stellar Nurseries . . . 99

1 Chapter 1 – Our Place in the Universe

1.1 Overview

A naive look at the sky, which seems to rotate around us, implies we live in a **geocentric** Universe, ie. that everything orbits around the Earth. We know now that this is untrue, but the path to this knowledge was a long one.

We can refer to our place in the Universe as our **cosmic address**, this is our **solar system**; which consists of the Sun and all objects that orbit it including rocky **asteroids** and icy **comets**. Our solar system, and all the stars we can see, make up a small portion of the **Milky Way** galaxy.

A **galaxy** is an island of stars in space containing anywhere between a few hundred million to trillions of stars. The Milky Way is a relatively large one, with 100 billion stars. We are located about halfway from the center of the Milky Way (the **galactic center**) to the edge of the **galactic disk**.

In summary: the Earth is a planet in the solar system, which is a collection of objects orbiting a star, which is in the milky way galaxy, which is a part of the **local group** of galaxies, which is part of the **local supercluster** of groups, which is somewhere in the **Universe**.

The local group contains about 40 galaxies, and is one of what we call **galactic clusters** – groups of galaxies with more than a few members. Superclusters are essentially clusters of galactic clusters, as the Universe seems to be arranged ingiant chains and sheets with large divides between them. The local group is on the edge of the local supercluster.

1.2 The Big Bang and the Expanding Universe

We have observed that the Universe seems to be *expanding*, that is, the distance between galaxies is increasing. By extrapolating backwards, we imagine that all matter must ahve existed at the same point in the past and exploded outward in a **Big Bang**. Based on the rate of expansion, we believe this happened approximately 14 billion years ago.

Note that though the distance between galaxies is increasing, the distances between objects within galaxies is *not*.

Most galaxies, including our own, formed within a few billion years of the Big Bang.

1.3 The Birth of Stars

A star is **born** when gravity compresses the material in a cloud of gas and dust until it is dense and hot enough to generate energy through **nuclear fusion**. The star lives so long as it has useable material to fuel its fusion and dies once it runs out.

A star **dies** by blowing much of its remaining content back into space in a **supernova**. This matter eventually becomes new stars and planets.

1.4 Modelling the Universe

1.4.1 Distance

We can imagine our solar system shrunk down to a manageable size. On the **Voyage** scale (a model solar system in Washington, D.C. where sizes are one billionth of the actual size), the Sun is roughly the size of a grapefruit, Jupiter the size of a marble, Earth the size of a pinhead. Obviously the Sun is far larger than any planet, in fact, it has more than 1000 times as much mass as all the planets in our system combined. Note that the planets also vary in size to a large extent: the “permanent” storm on Jupiter known as the **Giant Red Spot** is larger than the Earth.

We can also use this model to describe the distances between objects. On the same scale, the Earth is 15m from the Sun and the distance from the Sun to pluto is 600m. To have enough space for the orbit of each object in the system, we would need a grid of 300 football fields centered around the Sun.

The closest star (Alpha Centauri) is incredibly far away, on this scale it would be the difference between Washington, D.C. and California.

If we reduce this scale by another factor of one billion, we can start thinking about the size of the galaxy. On this scale, each light year is roughly a millimeter and the Milky Way is about the size of a football field. The distance between our star system and Alpha Centauri is smaller than the width of our pinky.

1.4.2 Time

We can also model the time between events by creating a **cosmic calendar**. If we set the Big Bang as January 1^{st} and the present day as Decembre 31^{st}, we can place each major event on specific days. By the age of the universe, each month represents just over a billion years.

On this scale, the Milky Way was formed sometime in February. Our solar system, though was, only formed in September – life on Earth flourished by the end of that month. Recognizeable animals only appeared in mid-December. Dinosaurs first appeared the day after Christmas and died off yesterday. Around 9PM today, early hominids began to walk upright.

The entire history of human civilization, then, occurred in the last half-minute of January 31^{st}.The Egyptians built the pyramids in 11 seconds, Galileo proved the Earth orbited the Sun one second ago, and the average college student was born 0.05 seconds ago.

1.5 Motion of the Universe

The Earth has a daily rotation (its **spin**) and a yearly **orbit** (or **revolution**) around the Sun.

The Earth rotates each day around its **axis**, the imaginary line from the North to the South pole. It rotates from West to East – counter-clockwise when viewed from above the North pole. The speed is substantial; anywhere other than near the axes, an object whirls around the Earth at a speed greater than 1000km/h.

The Earth's average orbital distance is one **Astronomical Unit** (AU), which is approximately 150 million kilometers. At times, we race around the Sun in excess of one hundred thousand kilometers per hour.

Earth's orbital path defines the **eliptic plane**, and its axis is tilted by 23.5 degrees from a line perpendicular to this plane. The **axis tilt** happens to align our north pole with Polaris, the North Star.

Note that the Earth orbits the Sun in the same direction as it spins around its axis since it was formed from a spinning disk and both of these rotations are a remnant of this.

We also move relative to nearby stars at a rate of $70,000$ kilometers per hour. We rotate around the Milky Way's galactic center once every 230 million years, which implies speeds of (on average) $800,000$ kilometers per hour.

1.6 Dark Matter and Dark Energy

Since stars at different distance from the galactic center orbit at different speeds, we can learn how mass is distributed in the galaxy by measuring the differing speeds. Studies show that the mass of the stars in the galactic disk form only a small percentage of the total mass of the galaxy. Most of the galactic mass, then, seems to be located outside of the visible disk in the galaxy's **halo**. We call this mass **dark matter**, since we have not observed light being emitted from it. Similarly, we find that the bulk of the energy in the universe is **dark energy**. This seems to be the case in all observable galaxies.

1.7 Relative Galactic Movements

Within the local group, some galaxies move toward us and some move away. Outside of the local group, though, this changes; virtually every galaxy outside of the local group seems to be racing away from us at a speed proportional to its distance from us. This is the basis of our theory that of an **expanding universe**: that the space between galaxies is increasing.

Note that we observe this motion by measuring **Doppler shifts**, as detecting any difference in celestial position within our lifetimes is impossible.

2 Chapter 2 – Discovering the Universe

2.1 The Motion of the Stars

Stars appear to move across the sky from east to west. This is not, as the ancients believed, because everything revolves around the Earth, but because the Earth is rotating. This rotation is not perfect though, because the Earth is tilted.

Some stars (those near the celestial north pole) do not rise or set; they remain above the horizon and make daily counter-clockwise circles around the pole. These stars are called **circumpolar** stars. Other stars (those near the celestial south pole) never rise at all. All other stars appear to rise and set each day.

2.2 Constellations

Although we have a colloquial definition of constellations, astronomers more precisely declare **constellations** to be regions of the sky with well-defined borders. The patterns of stars which "form" constellations simply help us to locate them.

There are 88 official constellations which cover the night sky, as determined by a 1928 summit including members of the International Astronomical Union. Every part of the sky is located within one of these constellations.

Though the stars are very far away, the ancient Greeks believed they were all "painted" on a **celestial sphere** centered around the Earth. We use this today to help us map out space:

- the **north celestial pole** is directly above the north pole, and
- the **south celestial pole** is directly above the south pole, and
- the **celestial equator** mirrors the real equator, and
- the **ecliptic** is the path the Sun takes as it appears to circle around the celestial sphere yearly. It crosses the celestial equator at a 23.5 degree angle

The **Milky Way** traces a complete circle around the celestial sphere, moving through many constellations. It is almost, but not quite, repesentative of the Milky Way *Galaxy*: it traces our galaxy's disk of stars as it appears from our location in the outskirts of the galaxy. The Milky Way appears somewhat wider as we look through Sagittarius since this is the direction of the galactic center.

Note that when looking above you at the **local sky**, you can (obviously) only see one hemisphere of the celestial sphere at a time. We define the Earth-sky boundary as the **horizon**, the point directly overhead as the **zenith**, and an imaginary semi-circle passing along the sphere from due north to due south through the zenith as the **meridian**.

We can locate any object by its direction along the horizon and its altitude above the horizon. We also sometimes use the **azimuth** – the angular distance clockwise from due north.

We can define the **angular size** of an object as the angle it appears to span within our field of view. Since this depends on distance, it does not give us a clear idea of an object's true size; for example, the angular size of both the Sun and the Moon is half a degree despite the Sun being about 400 times larger (since the Sun is 400 times farther away).

The **angular distance** between two objects is the number of degrees which appears to separate them. The distance between the pointer stars in the big dipper is roughly 5 degrees. We further divide each degree into 60 **arcminutes** – and then each of those into 60 **arcseconds** – for precision.

2.2.1 Variance

Constellations vary with both our north-south location on Earth as well as the time of year.

Latitude affects the constellations by changing the locations of the horizon and zenith of our local sky. In effect, by moving to the north or south we can change which portion of the celestial sphere is visible. We can also use this effect to prove that *the altitude of the celestial pole in your sky is equal to your latitude*.

The constellations vary over the course of the year due to Earth's changing position around the Sun. As we orbit, the Sun appears to move across the eliptic such that different stars are behind it at different times of the year. The constellations along this eliptic make up the **zodiac**, the thirteen most widely known constellations (traditionally, there are twelve zodiacs; however, Ophiuchus is also present in the eliptic).

2.3 Seasons

The seasons are caused by the tilt of the Earth's axis. In effect, the axis remains pointing at a specific direction in space at all times. This, of course, means it is pointing at different points relative to the Sun throughout the year. The Northern Hemisphere is tipped toward the sun in their summer (June), and vice-versa. This causes the Sun's rays to hit the "closer" hemisphere for a longer time each day during their summer, as well as concentrating its rays, thus making it warmer.

Note that the common assumption is the summer occurs when the Earth is closer to the Sun than it is during winter. This is incorrect; in fact, the orbital distance between the Earth and the Sun *does* vary, but only by approximately 3%. This difference does not cause noticeable temperature changes.

2.3.1 Solstices

We mark the special celestial events each year as the **solstices** and **equinoxes**:

- the **summer (June) solstice** occurs around June 21^{st}. It is the moment in which the Norther Hemisphere is tipped most directly toward the Sun.
- the **winter solstice** occurs around December 21^{st} and is precisely the opposite of the summer solstice.
- the **spring equinox** occurs around March 21^{st} and is the moment at which the Northern Hemisphere switchees from being slightly tipped away from the Sun to slightly toward the Sun.
- the **fall equinox** occurs around September 22^{nd} and is precisely the opposite of the spring equinox.

The exact dates vary each year by no more than a few days in either direction. In fact, our leap year system is designed precisely to ensure this is true.

The equinoxes are the only days of the year in which the Sun rises and sets exactly due East and West, as well as being the only days in which an equal amount of sunlight falls on both Hemispheres. The Sun rises and sets farther to the North on the Summer solstice side of the equinoxes, and farther South on the Winter solstice side.

We usually consider the solstices and equinoxes as the first day of the new season, despite the summer solstice, for example, being the longest day of the year – ie. the midpoint of summer? This is generally due to weather patterns; the solstices and equinoxes match the beginning of the new season's weather patterns. We also find the it takes some time to match the temperature of the Earth to the Sun's location, thus making us feel a lag behind what the Sun implies our temperature should be.

Note that te solstices are named opposite to the seasons in the Southern Hemisphere. For the equator, we find that the rainy seasons occur at the equinoxes and the dry seasons occur at the solstices.

2.4 Precession

Precession is a slow wobble of the Earth's tilt which affects our orientation in space. Each precession cycle takes approximately $26,000$ years and slowly changes where our poles point to in space. Today, our axis points toward Polaris, which we call the North Star. In approximately $13,000$ years, Vega will be in this location (ie. a bright star very near the pole's zenith). Most of the time, there is no North Star.

Precession, though, does not change the amount of tilt we have relative to the eliptic; we always have a 23.5 degree tilt, and so our seasons are not affected by precession.

Precession is caused by the effect of gravity on a rotating object which is not a perfect sphere. For the Earth, precession is caused by the competing effects of gravity from the Sun and the Moon attempting to "straighten out" our bulging equator.

2.5 The Moon

The Moon orbits the Earth once every $27.\bar{3}$ days. We can see that the Moon appears to move across the sky at half a degree (it's angular size) per hour. As it moves across the sky, its appearance and rising / setting times change according to its **lunar phase**, which is based on its position relative to the Sun as it orbits the Earth.

The change of appearance is based on the direction the Sun casts its light from. When the Moon, Earth, and Sun form a right-angle, the Sun casts its light in such a way that only half of the Moon is illuminated from the Earth's perspective. The lunar cycle takes 29.5 days to complete.

The Moon appears to fill in illumination starting from the right, then lose illumination from the same direction. We refer to completely dark Moons as **New Moons** and completely illuminated ones as **Full Moons**. **Crescent Moons** and **Gibbous Moons** (barely illuminated and almost fully illuminated, respectively) are refered to as **waxing** or **waning** depending on whether it is between a New Moon and a Full Moon or vice-versa. Half-illuminated Moons are referred to as the **First and Third Quarter Moons**.

Moon Phases & Time of Day

Moon Phase	Name	Direction (From Sun)	Rising (Eastern Sky)	Meridian (Highest point)	Setting (Western Sky)
	New	0° away (in front)	6 AM	12 PM	6 PM
	First Quarter	90° East (6 hrs behind)	12 PM	6 PM	12 AM
	Full	180° away (opposite)	6 PM	12 AM	6 AM
	Third Quarter	90° West (6 hrs ahead)	12 AM	6 AM	12 PM

2.5.1 Eclipses

Eclipses occur when the Sun, Moon, and Earth are aligned. A **lunar eclipse** occurs when the Earth lies between the other two, such that the Earth's shadow falls on and blacks out the Moon. A **solar eclipse** occurs when the Moon lies between the Sun and the Earth, so that the Moon block's our view of the Sun (ie. its shadow falls on us).

Since the Moon's orbit is slightly (5 degrees) inclined, eclipses do not happen each month. Eclipses, then, only occur when the Moon passes through the ecliptic; the two locations in which it does are referred to as the **nodes** of its orbit. These times are called **eclipse seasons**, and occur twice per year.

A lunar eclipse occurs when a full moon occurs near a node, a solar eclipse occurs when a new moon occurs near a node.

Since the Moon's shadow has both an **umbra** – the central area which completely blocks sunlight – and a **penumbra** – which only partially blocks sunlight – these eclipse can look extremely different. If the three objects line up perfectly, we can have a **total lunar eclipse**, in which the Moon is completely blocked during the period of **totality**. More likely is a **partial eclipse**, which only hides a portion of the Moon. Finally, we have **penumbral lunar eclipses**, which shade the Moon but do not completely blot it out.

During totality, the Moon is completely dark for typically less than an hour, save for the red ring around it formed because Earth's atmosphere bends some of the Sun's light toward the Moon (and, to a far lesser extent, due to **gravitational lensing**).

Similarly, we have total and partial solar eclipses based on whether you are within the Moon's umbra or penumbra. When the Moon is too far away for its umbra to even reach the Earth, we see an **annular eclipse**: a ring of sunlight surrounding the Moon when we are directly behind the umbra; otherwise, we see a partial eclipse.

Since the umbra moves across the Earth at a speed of $1,700$ km/h, an eclipse can last no more than a few minutes for any given location on Earth.

The location of the nodes in the Moon's orbit slowly change over time. This gives us an eclipse cycle of 18 years 11.3 days; we call this the **Saros Cycle**. Of course, this only tells us when eclipses will occur, not where they will be visible from on Earth or whether they will be total or partial.

2.6 Planets

We can see five planets with the naked eye: Mercury, Venus, Mars, Jupiter, and Saturn. Mercury is rarely visiable, and only near sunrise or sunset. Venus can often be seen shining brightly in the evening (in the West) or before dawn (in the East). Jupiter, when visible, is the brightest star at night. Mars is often recognizeable by its red hue. Saturn has no distinguishing features, but can be identified with star charts.

Planets have different paths of motion that do stars, which is why the word for planet in Greek means “wandering star”. The planets usually move Eastward through constellations, but sometimes go through periods of **apparent retrograde motion** for anywhere between a few weeks and a few months. This retrograde motion occurs when the Earth “passes” the other planet, ie. when their orbits are in line with the Sun.

Stellar parallax is the phenomenon of stars appearing to move at different rates given different angles; given the extremely great distances between us and the stars, this is not detectable by the human eye – though it can be detected by telescopes.

3 Chapter 3 – Ancient Astronomy

3.1 Ancient Roots of Science

Other lunar calendars remain roughly synchronized with solar calendars by taking advantage of an interesting coincidence: 19 years on a solar calendar is almost precisely 235 months on a lunar calendar. As a result, the lunar phases repeat on the same dates about every 19 years (a pattern known as the Metonic cycle).

The study of ancient structures in search of astronomical connections is called **archaeoastronomy**

3.2 Ancient Greek Science

Greek - To account for the fact that the Sun and Moon each move gradually eastward through the constellations, the Greeks added separate spheres for them, with these spheres turning at different rates from the sphere of the stars. The planets also move relative to the stars, so the Greeks added additional spheres for each planet. The **difficulty** with this model was that it made it hard to explain the apparent retrograde motion of the planets.

The **Ptolemaic model** - Each planet moves on a small circle whose center moves around the Earth. A planet following this circle-upon-circle motion traces a loop as seen from Earth, with the backward portion of the loop mimicking apparent retrograde motion. Despite its complexity, the Ptolemaic model proved remarkably successful: It could correctly forecast future planetary positions to within a few degrees of arc.

3.3 The Copernican Revolution

Copernicus - Discovered simple geometric relationships that allowed him to calculate each planets orbital period around the Sun and its relative distance from the Sun in terms of EarthSun distance. The models success in providing a geometric layout for the solar system further convinced him that the Sun-centered idea must be correct.

Keplers key discovery was that planetary orbits are not circles but instead are a special type of oval called an ellipse. The locations of the two tacks are called the foci (singular, focus) of the ellipse. The long axis of the ellipse is called its major axis, each half is called the semimajor axis. A circle is an ellipse with zero eccentricity, and greater eccentricity means a more elongated ellipse.

Kepler's first law - The orbit of each planet about the sun is an elipse with the sun at one focus. It is closest at **perihelion** and farthest at the point called the **aphelion**.

Kepler's Second Law - As a planets moves around its orbit it sweeps out equal areas in equal times. This means the planet moves a greater distance when it is near perihelion than it does in the same amount of time near aphelion. That is, the planet travels faster when it is nearer to the Sun and slower when it is farther from the Sun.

Kepler's Third Law - More distant planets orbit the sun at slower average speeds. $p^2 = a^3$ p is the orbital period in years, and a is the distance from the sun. We can use the law to calculate a planets average orbital speed.

Galileo - observed four moons clearly orbiting Jupiter, not Earth. Soon thereafter, he observed that Venus goes through phases in a way that proved that it must orbit the Sun and not Earth.

Galileos experiments and telescopic observations overcame remaining objections to the Copernican idea of Earth Venus as a planet orbiting the Sun. Although not everyone accepted his results immediately, in hindsight we see that Galileo sealed the case for the Sun-centered solar system.

Science generally exhibits three hallmarks: (1) Modern science seeks explanations for observed phenomena that rely solely on natural causes. (2) Science progresses through the creation and testing of models of nature that explain the observations as simply as possible. (3) A scientific model must make testable predictions about natural phenomena that would force us to revise or abandon the model if the predictions do not agree with observations.

A **scientific theory** is a simple yet powerful model that explains a wide variety of observations using just a few general principles, and that has survived repeated and varied testing.

4 Chapter 4 – Motion, Energy, and Gravity

velocity speed with respect to a direction

acceleration rate of change in velocity

the acceleration of gravity $g = 9.8\frac{m}{s^2}$

momentum $p = mv$

net force net force acting on an object dictates changes in its momentum

mass amount of matter in object

weight force that a mass exerts on the ground (due to gravity and other forces, like elevators)

freefall state of falling without any resistance to slow you down. Since there is no ground for your mass to exert force upon, you seem weightless. Object x in orbit of object y is in a constant state of freefall toward y

Newton's Laws
1. If net force is zero, objects maintain velocity
2. Force is mass times acceleration
3. Forces have equal and opposite reaction forces

- Conservation of Angular Momentum
  - total angular momentum can never change
  - an object's angular momentum must transfer to or from another object
  - angular momentum of an object = radius of the orbit * velocity around the orbit * mass
  - this explains
    1. why Earth needs no fuel or push to continue orbiting the sun
    2. why Earth's velocity around the sun must be faster when it is closer to the sun (Kepler's Law)
  - The same is true for Earth rotating on its axis, though it is slowly transerring this rotational angular momentum to the Moon
- Conservation of Energy
  - energy also cannot change, only transferred and converted
    * kinetic: movement
    * radiative: carried by light (visible or otherwise)
    * potential: stored in some form (eg gravitational potential)
    * thermal: subcategory of kinetic, sum movement of particles within (measured in Kelvin)
    * mass: a type of potential energy (energy = mass * speed of light^2)
- Universal Law of Gravitation
  - every mass attracts every other mass in the universe
  - $G = 6.67 * 10^{-11} \frac{m^3}{kg*s^2}$
  - d = distance between object 1 and 2
  - $F = \frac{G*m_1*m_2}{d^2}$

bound orbits an object goes around another object over and over again (planets, satellites, moons)

unbound orbits paths that bring an object close to another object just once (some outer comets)

- Newton's Version of Kepler's Third Law
  - orginally $p^2 = a^3$
  - a = average orbital radius
  - p = orbital period
  - Newton: $p^2 = a^3 * \frac{4\pi^2}{G(m_1+m_2)}$
  - note: if m1 ¿¿ m2, you may be able to ignore m2 for an approximate answer (easier expression manipulation)

Orbital Energy the sum of an object's gravitational potential and kinetic energy. this value remains constant

Gravitational Encounter two objects pass near enough so that each can feel the effects of the others gravity. Note: gravitational encounters are the basis for slingshot maneuvers in spacecraft

- Atmospheric Drag
  - low-orbiting objects (few hundred km) experience slight drag
  - causing it to slow, converting to thermal energy
  - as it slows its orbit becomes smaller, eventually crashing to the surface
- Escape Velocity
  - if an object in bound orbit gains velocity (eg thrust) its orbit increases average altitude
  - an object with velocity of 11000 m/s (on surface) will escape Earth's gravity
  - this velocity does not depend on mass
  - since gravity weakens with distance, starting higher requires less energy
- Tides
  - the moon can pull the water on the surface towards it
  - strongest on the side of Earth facing the moon, causing a bulge
  - weakest on far side of Earth, causing another bulge
  - Sun also has an effect on tides, but is too far away to be as noticeable (little under half of moon's)
  - spring tides (sun and moon work together) and neap tides (sun and moon fight)
  - moon's synchronous rotation caused by tidal friction
  - used to rotate faster, tidal bulges in its mass
  - tidal forces cause the axial rotation to slow (and orbit radii to increase)

5 Chapter 5 – Light

- light spectrum
  - the range of visible light we see as we pass it through a prism
  - can be detailed enough to show us individual black bands representing missing colors
- electromagnetic spectrum: the complete version of all light forms. visible light is only tiny fraction
- wave properties
  - a wave is something that can transmit energy without having to carry material with it
  - wavelength: the distance between adjacent peaks (measured in m)
  - frequency: the number of cycles per second (measured in Hz)
  - since light can affect both charged particles and magnets, we refer to it as an electromagnetic wave
- All light travels at the same speed: $3 * 10^8 m/s$
- particle properties
  - comes in pieces called photons
- gamma — x-ray — ultraviolet — visible — infrared — microwave — radio
- atomic structure
  - protons, neutrons, electrons
  - some really obvious shit
  - strong nuclear force holds protons and neutrons together at the nucleus
  - electrons in an atom a cloud that surrounds the nucleus and gives the atom its apparent size
  - it is impossible to pinpoint their positions
  - isotopes: atoms with varying numbers of neutrons
- light and matter interact in four ways
  1. emission: matter creates light (eg thermal, electrical potential)
  2. absorption: light's energy is absorbed into matter (typically as thermal)
  3. transmission: matter allowing light to pass through
  4. reflection: light bouncing (scattering is reflecting randomly)
- transparent: material allows light to pass through
- opaque: material absorbs all light

- some materials treat certain light differently (eg red glass allows red light through, grass reflects green light)
- types of spectrum
  - continuous: broad range of wavelengths without interruption
  - emission line: light composed of individual bands (dependant on composition and temperature)
  - absorption line: broad range with individual bands missing
- electrons can only have particular amount of energy and not levels inbetween (measured in eV)
- 1 electron Volt = $1.60 * 10^{-19}$ Joule

These values are unique to every atom, ion, and molecule. Example:

```
A hydrogen atom has states:
    level 1: 0 eV   ground
          2: 10.2
          3: 12.1
          4: 12.8
 ionization: 13.6   escape
```

- an electron rising or falling between levls are called energy level transitions
- can only occur when an election gains or loses the specific amount of energy separating the two levels
- electrons will not accept energy in quantities that do not correspond with an energy level (except escape, can go over)
- each possible downward energy level transition (eg 3 to 1) corresponds to a release of energy in the form of photons
- the more energy released, the shorter the photon wavelength
- some of these transitions create photons with wavelengths that fall in the visible light spectrum (many won't be visible)
- the exact possible emissions are unique to each atom, so we can use emission lines to identify compositions of light sources
- electrons will not rest at high energy levels, they will fall back down quickly (fraction of a second)
- energy exchanges typically caused by atoms colliding
- most just bump away, a few transfer exactly the right amount of energy to an electron
- collisions only keep happening while the gas is relatively hot
- energy can also be recieved in these exact quantities by other photons

- this causes absorption lines, since the photons that get absorbed then released will be in random directions
- the photons that do not get absorbed travel straight through the material to us
- most objects (eg rocks, plants, people) are complex enough that they absorb light from a very broad range
- light cannot easily pass through, light emitted cannot easily escape

Consider an idealized case, an object absorbs all photons and does not allow photons inside it to escape easily. Photons bounce randomly around inside the object, constantly exchanging energy with its atoms or molecules. When photons finally escape the object, their radiative energies have become randomized so that they are spread over a wide range of wavelengths. This wide range explains why the spectrum of light from such an object is continuous, like a pure rainbow without any absorption or emission lines

- this all depends on the temperature of the object (the average kinetic energy of the atoms)
- that's why this type of light is called thermal radiation
- no real object emits a perfect thermal radiaton spectrum, but all objects emit light that approximates it
- two laws of thermal radiation:
  1. each square meter of a hotter objects surface emits more light at all wavelengths
     - each square meter on a hotter star emits more light at every wavelength than a cooler star
     - hotter star emits light at some ultraviolet wavelengths that the cooler star does not emit at all
     - T = temperature (in Kelvin)
     - $o = 5.7 * 10^{-8} \frac{W}{m^2K^4}$
     - emitted power per square meter of surface = oT^4
  2. hotter objects emit photons with a higher average energy
     - shorter average wavelength
     - explains why peak wavelength is shorter in hotter objects
     - Lambda Peak = $2.9 * 10^6 \frac{1}{T}$
- Doppler effect
  - the velocity of the light source have an effect on the apparent wavelength of the photons
  - travelling away: wavelengths appear longer, become redshifted
  - travelling towards: wavelengths appear shorter, become blueshifted
  - v = velocity of source (in radial direction, so only net away from us. negative means towards)

  - c = speed of light ($3 * 10^8 m/s$)
  - Lambda Shift = observed wavelengths from source
  - Lambda Rest = lab recorded wavelengths of source's composition
  - v/c = (shift - rest) / rest
- telescopes have two properties
  1. light collecting area - total light telescope can collect at a time
  2. angular resolution - smallest angle we can determine two stars are distinct
- arcminute: 1/60th of a degree
- arcsecond: 1/60th of an arcminute
- human eye has angular resolution of 1 arc minute (objects se)
- basic telescope designs
  1. refracting telescopes
     - operates like eye, uses transparent glass lenses to collect and focus light
     - earliest telescopes built by Galileo
     - worlds largest has 1m lens, 19.5m tube, completed 1897
  2. reflecting telescopes
     - use large curved primary mirrors to gather light, small secondary mirror to reflect to a focus
     - majority of modern telescopes, size typically restricted by weight of primary mirrors
     - 5m Hale telescope on Mt. Palomar, San Diego (1948)
     - 8m Gemini telescope on Mauna Kea, Hawaii
     - 10m Keck telescopes in Hawaii
     - plans for 30m telescope in 2018
- Telescopes can be specially designed to recieve non-visible light
  - radio waves have large wavelengths, telescopes need to be large to get decent resolution
  - 305m Arecibo radio dish in Puerto Rico has only 1 arc minute
  - collecting high energy rays straight on will punch straight through the lens, possibly damaging it
  - need to catch them at a slight angle and deflect them into the focus
- Putting telescopes in space dodges atmospheric interference but is extremely expensive
  - bright day skys, light pollution, weather, air turbulence (causes eye-visible twinkling)
  - lower energy wavelengths are barely affected by atmosphere and can be built lower

    - most high energy wavelengths cant even reach the ground

- adaptive optics: computers control the telescopes, making minute adjustments to the shape of the mirrors many times a second to eliminate atmospheric distortion
- interferometry: using multiple telescopes simultaneously to combine their images to achieve higher resolution

6 Chapter 6 – Formation of Planetary Solar Systems

6.1 Overview

This chapter is about the nature of our solar system and current scientific ideas about its birth. We will also examine characteristics about our solar system that are key clues about how it formed. Finally it will talk about how astronomers have discovered other planets around other stars and how those planetary systems are helping us understand our own.

6.2 Clues to the formation of the Solar System

The Solar System's layout and composition offer 4 clues as to how it was born.

1. **Large bodies in the solar system have orderly motions**.
    - All planets have nearly circular orbits going in the same direction in nearly the same plane.
    - All planets **orbit** the Sun in the same direction: **counterclockwise** as viewed from high above Earths North Pole.
    - Most planets rotate in the same direction in which they orbit, with fairly small axis tilts. The Sun also rotates in this direction.
    - Most of the solar systems large moons exhibit similar properties in their orbits around their planets, such as orbiting in their plane
2. **Planets fall into two major categories**
    (a) **Terrestrial planets**
        - Small in mass and size
        - Close to the sun
        - Made of metal and rock
        - Few moons and no rings

    (b) **Jovian planets**
        - Large in mass and size
        - Far from the Sun

- Made from H, He and hydrogen compounds
- rings and many moons

3. **Swarms of asteroids and comets populate the solar system**. Vast numbers of rocky asteroids and icy comets are found throughout the solar system, but are concentrated in 3 distinct regions
   - Most **asteroids** orbit in the **asteroid belt** between Mars and Jupiter
   - Many **comets** are found in the **Kuiper Belt** beyond Neptune's orbit
   - Even more **comets** orbit the sun in the distant spherical region called the **Oort Cloud** and only a rare few ever plunge into the inner solar system. May contain a trillion comets.
4. **Several notable exceptions to these trends stand out**
   - **Uranus's odd tilt** Uranus rotates nearly on its side compared to its orbit and its rings and major moons share this sideways orientation.
   - **Earth's relatively large moon** Our moon is much larger in size than most other moons in comparison to their planets
   - Venus' backwards rotation

6.3 The Sun

The **sun contains more than 99.8% of the solar systems total mass**. (1000 times more massive than the rest of the solar system combined). The surface is a sea of rolling hot (5800K) Hydrogen and Helium gas. The sun is gaseous throughout and temperture and pressure both increase with depth. In addition, charged particles moving outward (**Solar wind**) help shape planetary magnetic fields and can influence planetary atmospheres.

6.4 Mercury

A desolate, cratered world with no active volcanoes, no wind, no rain, and no life. It is a world of both **hot and cold extremes**. The combination of rotation and orbit gives Mercury days and nights that last about 3 Earth months each. Mercurys **surface is heavily cratered** But it also shows evidence of past geological activity, such as plains created by ancient lava flows and tall, steep cliffs that run hundreds of kilometers in length. Mercurys **high density** indicates that it has a very large iron core.

6.5 Venus

Venus is nearly identical in size to Earth. It **rotates on its axis very slowly and in the opposite direction of Earth**, so days and nights are very long. An **extreme greenhouse effect** bakes Venuss surface to an incredible 470C. Day and night. Venus has **mountains, valleys, and**

craters, and shows many signs of past or present volcanic activity. But Venus also has geological features unlike any on Earth, and we see no evidence of Earth-like plate tectonics.

6.6 Earth

Only planet in our solar system with oxygen to breathe, ozone to shield the surface from deadly solar radiation, and abundant surface water to nurture life. Temperatures are pleasant because Earths atmosphere contains just enough carbon dioxide and water vapor to maintain a moderate greenhouse effect.

6.7 Mars

Mars has ancient volcanoes. The presence of dried-up riverbeds, rock-strewn floodplains, and minerals that form in water offers clear evidence that Mars had at least some warm and wet periods in the past. Major flows of liquid water probably ceased at least 3 billion years ago. More than a dozen spacecraft have flown past, orbited, or landed on Mars.

6.8 Jupiter

Most famous feature: long-lived storm called the Great Pluto. **Made primarily of hydrogen and helium and has no solid surface**. Increasing gas pressure would crush us long before we ever reached its core. Jupiter reigns over dozens of moons and a thin set of rings (too faint to be seen in most photographs).

6.9 Saturn

Saturn is made mostly of hydrogen and helium and has no solid surface. The rings may look solid from a distance, but in reality they are made of countless small particles, each of which orbits Saturn. Titan, the only moon in the solar system with a thick atmosphere. Saturn and its moons are so far from the Sun that Titans surface temperature is a frigid -180C.

6.10 Uranus

It is made largely of hydrogen, helium, and hydrogen compounds such as water (H 2 O), ammonia (NH3), and methane (CH4). Uranus lacks a solid surface. The entire Uranus systemplanet, rings, and moon orbitsis tipped on its side compared to the rest of the planets and it gives Uranus the most extreme seasonal variations of any planet in our solar system.

6.11 Neptune

Neptune looks nearly like a twin of Uranus, although it is more strikingly blue. Smaller than Uranus but more massive due to higher density (even though they have similar composition. Triton is the only large moon in the solar system that orbits its planet backwardthat is, in a direction opposite to the direction in which Neptune rotates. This backward orbit makes it a near certainty that Triton once orbited the Sun independently before somehow being captured into Neptunes orbit.

6.12 Pluto (and other dwarf planets)

Pluto is much smaller and less massive than any of the other planets, and its orbit is much more eccentric and inclined to the ecliptic plane. Its composition of ice and rock is also quite different from that of any of those planets, although it is virtually identical to that of many known comets. Pluto is not even the largest of Kuiper belt objects, Eris, is slightly larger than Pluto.

6.13 Where did the solar system come from?

The **nebular theory** begins with the idea that our solar system was born from a cloud of gas, called the solar nebula, that collapsed under its own gravity. As the solar nebula shrank in size, three important processes altered its density, temperature, and shape, changing it from a large, diffuse (spread-out) cloud to a much smaller spinning disk: **heating, spinning, flattening**. As it collapsed, it heated up, spun faster and flattened into a disk.

6.13.1 The Formation of the planets

In the center of the collapsing solar nebula, gravity drew together enough material to form the Sun. Because hydrogen and helium gas made up 98% of the solar nebulas mass and did not condense, the vast majority of the nebula remained gaseous at all times. However, other materials could condense wherever the temperature allowed.

The solid metal and rock in the inner solar system ultimately grew into the terrestrial planets we see today, but these planets ended up relatively small in size because rock and metal made up such a small amount of the material in the solar nebula. **Accretion** The process in which small “seeds” grow into planets.

The leading model for jovian planet formation holds that these planets formed as gravity drew gas around ice-rich “boulders” much more massive than Earth. Their large masses had gravity strong enough to capture some of the hydrogen and helium gas that made up the vast majority of the surrounding solar nebula. Ultimately, the jovian planets accreted so much gas that they bore little resemblance to the icy seeds from which they started.

The young Sun had a strong solar windstrong enough to have swept huge quantities of gas out of the solar system, sealing the compositional fate of the planets.

Asteroids and comets are leftover and are less common than earlier in the solar systems life. Although impacts occasionally still occur, the vast majority of these collisions occurred in the first few hundred million years of our solar systems history, during the period we call the **heavy bombardment**. These impacts did more than just batter the planets. They also brought materials from other regions of the solar system. (Potentially bringing water to Earth)

6.13.2 How do we explain the exceptions to rules?

Our moon - The giant impact hypothesis holds that a Mars-size object hit Earth at a speed and angle that blasted Earths outer layers into space. Strong support for this comes from two features of the moon's composition.

1. The composition of the moon is similar to Earth's outer layers
2. The Moon has a much smaller proportion of easily vaporized ingredients (such as water) than Earth. This fact supports the hypothesis because the heat of the impact would have vaporized these ingredients.

Other Exceptions

- Mercurys surprisingly high density may be the result of a giant impact that blasted away its outer, lower-density layers.
- Giant impacts could have also been responsible for tilting the axes of many planets (including Earth) and perhaps for tipping Uranus on its side
- Venuss slow and backward rotation could also be the result of a giant impact

Nebular Theory accounts for **all FOUR** of the major features of the solar system.

6.13.3 When did the Planet's form?

The planets begin to form just over **4.5 billion years ago**

6.13.4 Other Planetary Systems

We can detect planets in other stars directly (pictures) or indirectly (measurements of a stars properties).

Indirect Methods:

- **Astrometric Technique** - we make very precise measurements of stellar positions in the sky. If a star wobbles gradually around its average position (the center of mass), we must be observing the influence of unseen planets.
- **Doppler technique** searches for a stars orbital movement around the center of mass by looking for changing Doppler shifts in a stars spectrum. Used for the majority of planet discoveries to date

- **Transits and Eclipses** searching for slight changes in a stars brightness that occur when a planet passes in front of or behind it. The transit method can also be used to search simultaneously for planets around vast numbers of stars and to detect much smaller planets than is possible with the Doppler technique.

6.13.5 Comparing Extrasolar planets

Orbits

- Most of the planets orbit very close to their host star
- many of the orbits are elliptical instead of nearly circular like the orbits of planets in our own solar system

Masses

Most of the known extrasolar planets are more massive than Jupiter, smallest is twice the mass of Earth

7 Chapter 10 – Our Star

7.1 A Closer Look at the Sun

7.1.1 History

Our first views of the sun were that it was a ball of fire. In the 19^{th} century we had found the Sun's radius and distance and found that its energy could not have come from burning fuels or other chemical processes.

The first real idea was that the Sun generates energy by slowly contracting in size through **gravitational contraction**. Gravitational potential energy is converted into thermal energy as mass moves inward. This would keep the inside of the Sun hot. The amount of contraction required would be small enough to go unnoticed until the 19^{th} century. This theory shows that the Sun could continue contracting for 25 million years. The problem: geologists had already calculated the earth's age as much higher than that.

The next idea was based on Einstien's theory of relativity ($E = mc^2$). Calculations showed that the Sun had enough mass to shine for billions of years. This explained where sunlight came from, but not the thermal energy. Eventually in the 1930's the discovery of nuclear fusion was found and we use that to explain where thermal energy comes from.

7.1.2 Nuclear Fusion

Nuclear fusion requires very high temperature and density to start. This started in the sun through gravitational contraction. The sun was formed from a collapsing gas cloud. This released gravitational potential energy raisin the core temperature. This continued to happen until sustained nuclear fusion started.

The sun has a fairly steady size and energy today because it has reached equilibrium. **Gravitaitonal Equilibrium** is the balance between the outward push of hot internal gases trying to escape and the inward push of gravity. This allows the sun to have a steady size. This also means that **pressure increases with depth** in the sun. **Energy Balance** is the balance between the rate of fusion and the rate of energy being released from the Sun's core into space.

7.1.3 Structure

The sun is essentially a ball of plasma (gas in which atoms are ionized) which moves like a gas, but also reacts to magnetic fields.

Basic Properties:

Radius (R Sun)	696,000 km (about 109 times the radius of Earth)
Mass (M Sun)	2 10 30 kg (about 300,000 times the mass of Earth)
Luminosity/Power Output (L Sun)	3.8 10 26 watts
Composition (by percentage of mass)	70% hydrogen, 28% helium,2% heavier elements
Rotation rate	25 days (equator) to 30 days (poles)
Surface temperature	5800 K (average); 4000 K(sunspots)
Core temperature	15 million K

Layers (outside in):

- Solar wind
- Corona
- Chromosphere
- Photosphere
- Convection zone
- Radiation zone
- Core

Solar Winds is a stream of charged particles blown outward from the Sun. These help shape the magnetospheres of planets and the tails of comets.

Corona is suprisingly hot (1 million K) and emits the most X-ray radiation, the density is very low

Chromosphere is much cooler here (10,000 K), radiates UV radiation

Photosphere temperature is 6,000K, surface churns like boiling water, home of sunspots and intense magnetic fields

Convection Zone region of hot gas rising and cool gas sinking caused by energy from the core rising to the surface (called convection, duh)

Radiation Zone less turbulent than the convection zone, energy moves outwards as photons instead of hot gas, temperature rises to 10 million K, shit ton of X-ray radiation

Core where nuclear fusion is making energy, temperature 15 million K, density 100 that of water, pressure 200 billion times earth's surface, energy takes hundreds of thousands of years to get to the surface

7.2 Nuclear Fusion in the Sun

Note nuclear fusion (the Sun) $\neq$ nuclear fision (nuclear reactor).

Within the Sun's core there is a soup of hot fas funn of psitively charged atom nuclei flying about. When these collide (most of the time electormagnetic forces deflect them) they stick together to form a heavier nucleus. This is caused by **strong force** (binds protons and neutrons together) overriding the electromagnetic deflection force. It's only strong enough to do this at very small distances which happens due to the high speed of the particles (which is in turn caused by the high temperature which is caused by the high pressure which is caused by high gravitational force which is caused by large mass).

This is explained by the **Ideal Gas Law**

$$P = nkT$$

where P is the pressure, n is number density (particles per volume), T is temperature, and k is **Boltzmann constant** $= 1.38 \times 10^{-23}$ joule/K

7.2.1 Proton-Proton Chain

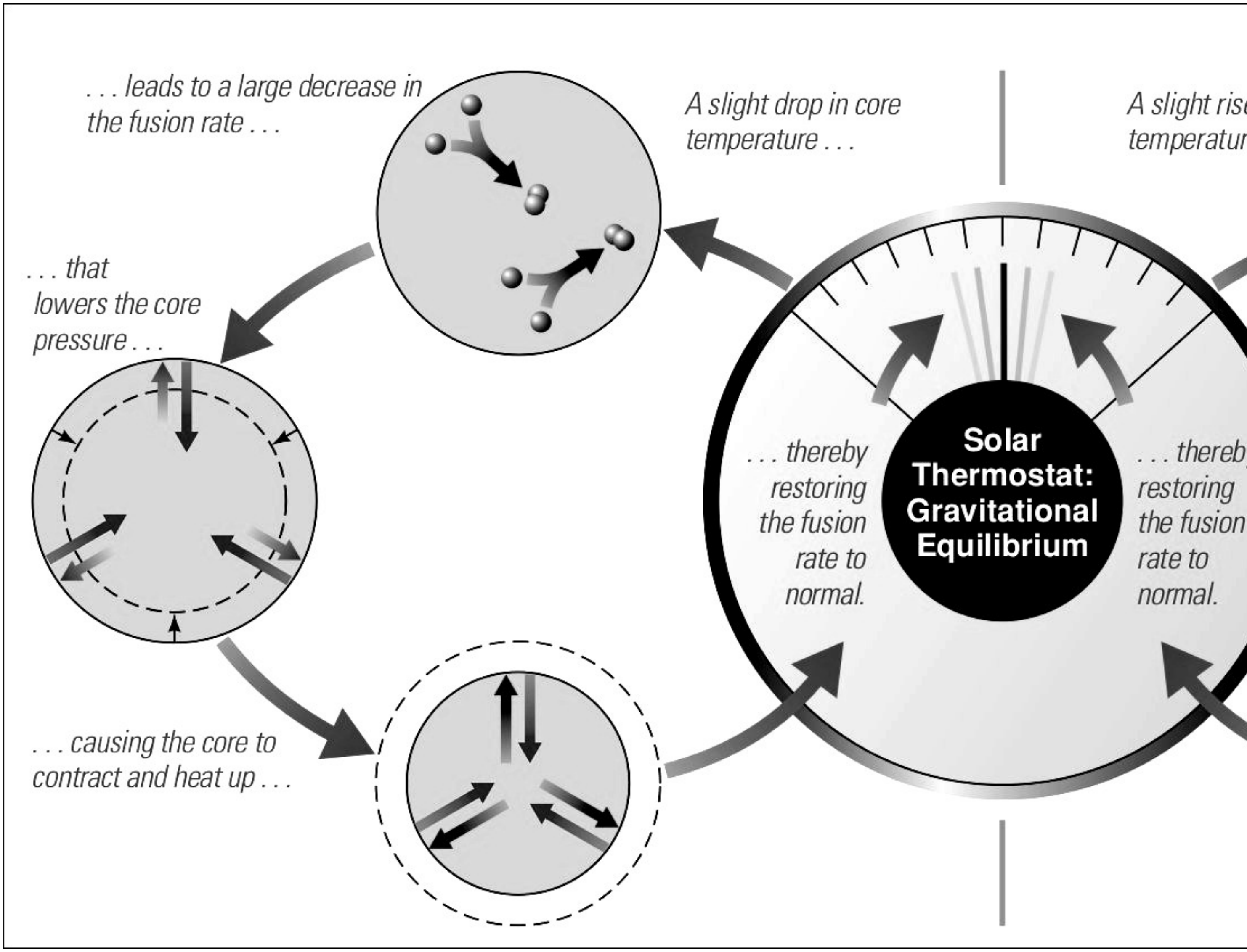
Most hydrogen comes in the form of a single proton, but we need to fuse it into a helium atom which is two protons and two neutrons. So what we have to do is fuse four hydrogen atoms into one helium atom. This is through a sequence of events called the **proton-proton chain**.

1. Two protons fuse to make a deuterium nucleus (1 proton and 1 neutron). This step occurs twice
2. The deuterium nucleus and a proton fuse to make a nucleus of helium-3 (2 protons, 1 neutron). This step occurs twice
3. Two helium-3 nuclei fuse to form helium-4 (2 protons, 2 neutrons), releasing two excess protons in the process.

In total four protons collide to make a helium atom, two positrons, and two neutrinos.

7.2.2 Solar Thermostat

Life on earth relies on the Sun's steady fusion rate. If we were to increase the core's temperature slightly, this would cause an increase in fusion rate. The increased fusion rate would make more energy, but energy moves very slowly through the sun so it would get bottled up in the core. This would increase the core pressure to exceed the balancing force of gravity so the core would expand and cool. Cooling lowers the fusion rate and equilibrium is reached again.



7.2.3 Path of Energy Through the Sun

Energy starts as photons in the Sun's core. They zigzag at the speed of light so it takes them a while to get out. In the dense interior a photon can only ravel a fraction of a millimeter before it collides with electron and gets deflected in a new direction causing its zigzag path. Eventually it makes its way through the core and radiation zone into the convection zone where the temperature drops to 2 million K and the photon is absorbed into cooler solar plasma. This creates the convection that happens in the convection zone. Eventually it rises to the top and enters the photosphere. Here the density is low enough that photons can escape into space as sunlight.

How do we know about the interior of a star:

- Mathematical models: based on laws of physics and observed properties

- Solar Vibrations: the Sun's surface vibrates like with earthquakes which we can see in Doppler Shifts.
- Solar Neutrinos: these are formed during nuclear fusion, these can pass through almost anything without reacting (including the Sun's layers), so we can see whats going on right now (well, 8 minutes ago)
  - these fuckers are hard to catch, need detectors deep in mines
  - initially we only caught a third of what we expected (solar neutrino problem) due to neutrinos changing properties during their journey (electron neutrino, muon neutrino, or tau neutrino)

7.3 The Sun-Earth Connection

7.3.1 Sunspots and Magnetic Fields

Sunspots are dark spots on the sun where things are cooler. They are formed when magnetic fields keep hot gas from entering a section of the photosphere. Magnetic fields can alter the energy levels of atoms (Zeeman effect), mucking with their spectral lines. The particles in solar plasma move along magnetic lines (usually spiraling along them).

Sunspots form where magnetic fields extend from the Sun's interior. The magnetic lines there are strong enough to suppress convection making the spot cool. They usually last a few weeks until their magnetic fields weaken. Sunspots tend to appear in pairs connected by a magnetic loop. Gas getting trapped in these loops makes **solar prominences**.

7.3.2 Solar Storms

These are sudden changes in the Sun's magnetic fields. The most dramatic example is **solar flares** which send bursts of X rays and fast moving particles into space. Flares tend to happen near sunspots. The current theory is that solar flares are caused when magnetic fields become so twisted they cannot bear the tension and snap into a better shape.

7.3.3 Heating the Chromosphere and Corona

Some weird shit goes down on the sun where its atmosphere gets hotter the farther you go out. The current theory is that magnetic fields carry energy upward to heat the chromosphere and corona.

The churning that happens in the convection zone probably shakes with tightly wound magnetic lines which carry this energy into the atmosphere and deposit it as heat.

Its very hard to investigate this because the solar atmosphere is not dense enough to see at that point (except during an eclipse). We can watch them through X-rays and UV rays.

In X-ray images of the chronosphere:

- bright spots is where hot gas is trapped below a sunspot where magnetic lines loop back to the Sun
- dull spots (**coronal holes**) are under magnetic lines that escape into space
- the stuff blown out by flares are huge bubbles called **coronal mass ejections**
  - have strong magnetic fields
  - causes auroras
  - fuck with satellites

7.3.4 Solar Cycles

Sunspots have a 11 year cycle. The solar maximum has most sunspots and solar minimum has fewest. At each solar maximum the Sun's magnetic fields start to flip. This is because all magnetic lines connecting pairs of sunspots point the same direction. This means that magnetic fields have a 22 year cycle.

8 Chapter 11 – Surveying the Stars

8.1 Properties of Stars

8.1.1 Luminosity

The **apparent brightness** of a star is how bright it appears to us, or the amount of power reaching us per unit area (units are watts per square meter). The **luminosity** of a start is is the total power that the star emits (units are watts). Apparent brightness follows a inverse square law to distance.

$$\text{apparent brightness} = \frac{\text{luminosity}}{4\pi \times (\text{distance})^2}$$

The most direct way to measure a star's distance it through measuring its stellar paralax. This is found by comparing a star's shift against its background over 6 months. We calculate its **paralax angle**

$$d = \frac{1}{p}$$

Where d is the distance to that star in light years and p is the paralax angle (Note: 1 arcsecond $\rightarrow$ 3.26 lightyears = 1 parsec)

We tend to measure luminosities as orders of magnitude of our sun's luminosity, called **apparent magnitude** instead of apparent brightness and **absolute magnitude** instead of luminosity. For every 5 magnitudes we have a brightness factor of 100. So a magnitude 1 star is 100 times brighter than a magnitude 6 star. We define the absolute magnitude as the apparent magnitude if owould have itf it were at a distance of 10 parsecs.

8.1.2 Temperature

The temperature of a star usually means its surface temperature since its the easiest to measure. A star's temperature is easier to measure than luminosity since it does not vary with distance. We can measure a star's temperature with reasonable accuracy by measuring its color. This is done by comparing its apparent brightness in two different colors of light (usually blue and red).

We run into problems when interstellar dust interferes with the color of a star so astronomers use a star's spectral lines instead. Stars showing spectral lines of ionized elements are fairly hot because it takes high temperature to ionize atoms. In contrast, stars displying spectral lines of molecules are relatively cool. Stars are classified by their **spectral type** OBAFGK in decreasing order of temperature. These are often divided farther using numbers. For example our sun is a G2 star meaning its hotter than a G3 but cooler than a G1.

Spectral Type	Example(s)	Temperature Range	Key Absorption Line Features
O	Stars of Orions Belt	¿30,000 K	Lines of ionized helium, weak hydrog
B	Rigel	30,000 K10,000 K	Lines of neutral helium, moderate hy
A	Sirius	10,000 K7500 K	Very strong hydrogen lines
F	Polaris	7500 K6000 K	Moderate hydrogen lines, moderate l
G	Sun, Alpha Centauri A	6000 K5000 K	Weak hydrogen lines, strong lines of
K	Arcturus	5000 K3500 K	Lines of neutral and singly ionized m
M	Betelgeuse, Proxima Centauri	¡3500 K	Strong molecular lines

History of Spectral Types Spectral types were made at Harvard College by Edward Pickering's computers (women who'd studied physics or astronomy). The first was Williamina Flemming who classified A-O by the descending strength of hydrogen lines. Annie Jump Cannon modified this existing classification by reordering and removing classes until the OBAFGKM that is used today was left. Finally Cecilia Payne-Gaposchkin discovered that stars were all made of the same material and the lines reflected ionization levels which indicated surface temperature.

8.2 Mass

Measuring mass is very difficult and we can only really do it on binary star systems. We do this by applying Newton's version of Kepler's third law

Binary star types:

- **visual binary:** we can see each star distinctly, sometimes one star is too dim to see but we can observe the shift of the visible star
- **eclipsing:** a pair of stars that orbit in a plain of our line of sight, we rotate between seeing the combined light of both stars (no eclipse) and only the light of one star (full eclipse)
- **spectroscopic:** we need to use Doppler shifts to detect its nature

8.3 Patterns Among Stars

These are ways of charting stars, the x-axis is the surface temperature (OBAFGKM) and the vertical axis is luminosity (L_{sun}) on a logarithmic scale. We can also infer the star's radius from the chart because a star's luminosity is based on its surface temperature and radius.

$$L = 4\pi r^2 \times \sigma T^4 \sigma = \qquad 5.7 \times 10^{-8} \text{watt}/(m^2 \times \text{Kelvin}^4)$$

Where L is luminosity, r is radius, σ is amount of thermal radiation emmited per unit area constant, and T is the star's temperature. This means that the radius of a star increases along a diagonal from lower left to upper right.

Stars cluster on the H-R diagram:

- **main sequence:** streak running from upper left to lower right
- **supergiants:** upper right
- **giants:** between supergiants and main sequence
- **white dwarfs:** lower left

Like with spectral classes, astronomers assign luminosity classes describing the region of the H-R diagram that a star falls in. I is for super giants, III is for giants and V is for main sequence. II and IV are for those that fall inbetween. White dwarfs fall outside the classification and are called wd. Stars with higher luminosity have larger radii as well.

We combine spectral type and luminosity class together to identify stars.

8.4 Main Sequence

Main sequence stars are the majority of stars that we observe and because of that we have found more patterns within them. Mass increases as we go up the strip of main sequence stars on the H-R Diagram. We also see that low mass stars are much more common than high mass stars. Mass is the most important attribute of hydrogen fusing stars because it determines the balance point at which energy released by fusion equals the energy lost from the star's surface. This is what allows for the wide range of luminosities. Luminosity is very sensitive to mass (example a star 10 times as massive as the sun is 10000 times as luminous).

A luminous star must be very hot or very large. But a very small mass change is required to greatly increase the luminosity of a star, so their surface temperature must be much higher to account for this large increase in luminosity. This fits the H-R Diagram pattern of temperature increasing with luminosity. We can use the mass-luminosity-temperature relationship to estimate a star's mass just by knowing its spectral type.

A star is born with a set amount of hydrogen fuel, the amount of time that it can burn this fuel for is the star's **main sequence lifetime**. Lifetime is inversely proportional to the mass of the star. This is because as mass increases luminosity increases exponentially, so stars with higher masses may have more fuel but they burn it waaaay faster.

8.5 Giants, Supergiants, and White Dwarfs

8.5.1 Giants and Supergiants

These are much cooler but more luminous than the sun which tells us that they are huge. These stars have almost exhausted their hydrogen fuel supply and are trying not to collapse under their own weight. They do this by releasing fusion energy at a high rate which explains their high luminosity, and the need to radiate all this energy expands them to enormous size.

8.5.2 White Dwarfs

This is what happens when a giant runs out of fuel completely. The star ejects all of its outer layers and is left only with a dormant core. They are hot because they are still the core of a star, but dim because they have no way to radiate their energy.

8.6 Star Clusters

Stars are born from giant clouds and many stars can be born from the same cloud, so they tend to cluster.

- all stars in a cluster are about the same distance from earth
- all stars in a cluster are about the same age

8.6.1 Types of clusters

- **open cluster:** found in disk of galaxy, young stars, up to several thousand stars, about 30 light years across
- **globular cluster:** found in halo of galaxy: oldest stars, more than a million stars, 60-150 light years across

8.6.2 Age of a Cluster

We plot a cluster's stars on the H-R Diagram, and this tells us its age. For instance the Pleides open cluster has no stars of the O spectral class. This means that Pleidas is old enough that its O stars have finished their hydrogen fission and 'died'. We call the point at which a cluster's main sequence diverges from the standard main sequence the **main sequence turnoff**. The age of the cluster is equal to the lifetime of stars at its main-sequence turnoff point (at its most massive star).

9 Chapter 13 – White Dwarfs, Neutron Stars, Black Holes

To scientists, dead stars are ideal laboratories for testing the most extreme theories of general relativity and quantum theory.

9.1 White Dwarfs

9.1.1 What is a white dwarf?

A white dwarf is essentially the exposed core of a low-mass star that has died and shed its outer layers in a planetary nebula. It is quite hot when it first forms (it was the inside of a star) but it slowly cools with time. White Dwarfs have masses like those of stars but sizes like that of Earth which is why they are generally quite dim compared to stars like the sun. THe hottest white dwarfs can shine brightly in high-energy light such as ultraviolet and X-rays.

A white dwarf's combination of starlike mass and a small size makes gravity near its surface very strong. Because there is no fusion to maintain heat and pressure, **degeneracy pressure combats the gravitational force. The same pressure supports brown dwarfs, it arises when particles are packed as closely as the laws of quantum mechanics allow. More specifically, in white dwarfs arises from electrons so it is called electron degneracy pressure**

9.1.2 Composition, Density and Size

Composition of a White Dwarf reflects product's of stars final fusion stage. A white dwarf from something resembling our sun would consist mostly of carbon. (stars like the sun fuses helium into carbon in final stage of life). The bf denisty of a white dwarf is so high that a teaspoon of its material would weight several tons. More massive white dwarfs are also smaller in size (the most massive being the smallest). The more massive a white dwarf is, the greater gravity compresses matter to a much greater density. Electrons in a white dwarf respond to compression by moving faster.

9.1.3 The White Dwarf Limit

The fact that electron speeds are higher in more massive white dwarfs leads to a fundamental limit on the maximum mass of a white dwarf. The White Dwarf limit is $1.4 M_Sun$ **because anything larger than this would have electrons moving faster than the speed of light. Also called Chandrasekhar limit. In every observed case this limit holds true.**

9.1.4 White Dwarf in a binary System

A white dwarf in a binary system can slowly gain mass if its companion is a main sequence of giant star. Matter coming from the other star forms a whirlpool like disk

as it makes its way to the White Dwarf's surface (called an accretion disk). In this way, a white dwarf can get Hydrogen.

Novae: Hydrogen spilling towards the white dwarf heats up. If the temperature reaches 10 million K hydrogen fusion suddenly ignites. This thermonuclear flash causes the binary system to shine for a few weeks as a nova. (far less luminous than a supernova but can still shine as brightly as 100,000 suns). Accretion resumes after nova explosion subsides so process can repeat itself

White Dwarf SuperNovae: Through repeating the previous process it is believed that a white dwarf gains mass. When it reaches the white dwarf limit carbon fusion begins and explodes completely into what we call a White Dwarf Supernova. This is however quite different from a massive star supernova. Both shine with luminosities of 10 billion times that of the Sun but white dwarfs supernovas fade steadily and massive stars are more complicated. White Dwarf supernovas also lack hydrogen lines.

9.2 Neutron Stars

9.2.1 What is a neutron star?

A ball of neutrons created by the collapse of the iron core in a massive star supernova. Typically 10km in radius yet more massive than the sun. Neutron degeneracy pressure supports neutron stars. The gravity on the surface makes the escape velocity about half the speed of light. Neutron stars spin rapidly when they are born and strong magnetic fields can direct beams of radiation that sweep through space.

9.2.2 How were they discovered?

First observational evidence 1967, radio waves at precise intervals (now refered to as pulsars). Signal came from gaseous remains of supernova. It was a neutron star, pulsations arise becuase of conservation of angular momentum (rotation increases as size decreases). Neutron star's rotation slows over time. Pulsars must be neutron stars because no other object could spine that quickly without tearing itself apart. White Dwarf 1/sec. Pulsar as fast as 625/second.

9.2.3 Neutron Star in a binary System

Like white dwarfs, neutron stars can burst back to life. Due to stronger gravity, the accretion disk on a neutron star is much hotter and denser than a white dwarf's. High temperatures in inner regions of the disk make it radiate powerfully in x-rays. Due to this emission these are often called X-ray binaries and hundreds have been detected in the Milky Way. Pulsars of X-ray binaries accelerate with time, some rotating every few thousandths of a second. (called millisecond pulsars).

Helium fusion can happen at a layer of the disk builds to 100 million K. Helium fuses rapidly and generates an X-ray burster which lasts a few seconds and flares every few hours to every few days. Energy relased is 100,000 times more powerful than sun output, all in X-rays. After burst, accretion resumes.

9.3 Black Holes

9.3.1 What is a Black Hole?

A black hole is so compact that it has an escape velocity greater than the speed of light, neither light nor anything else can escape from within a black hole. They are actually spherical and not funnel shaped.

The Event Horizon: The boundary between the inside of a black hole and the universe outside is called the event horizon. It marks the point of no return for objects, the boundary at which escape velocity equals the speed of light. Gets the name because we have no hope of learning about events that occur within it.

The size of a black hole is usually the size of its event horizon, defined by the Schwarzschild radius. Black hole with mass of the Sun has a Schwarzschild radius of about 3km. More massive black holes have a larger Schwarzschild radius.

A collapsing stellar core becomes a black hole at the moment it shrinks to a size smaller than its Schwarzschild radius.

Schwarzschild radius:

$$R_s = \frac{2GM}{c^2}$$

9.3.2 Singularity and Limits of Knowledge

Because nothing can stop the crush of gravity in a black hole, we might expect all matter that forms a black hole must ultimately be crushed to an infinitely tiny area and dense point in the center called a singularity

According to Einstein's theory from your point of view a friend would never cross the event horizon even though he would vanish from view due to redshifiting. You would not survive to cross the event horizon due to gravity, however with supermassive black holes, tidal forces are weaker so it would be possible to enter the event horizon.

9.3.3 Formation of a Black Hole

Most massive stars may not succeed in blowing away all upper layers in supernova. If enough mass falls back to neutron star, it could exceed neutron star limit (3M Sun). Gravity would exceed degeneracy pressure and core collapses again with no known force to keep it from collapsing into a black hole.

9.3.4 Observational Evidence

Gravity alters its surroundings. Compelling observational evidence comes from studying X-ray binaries, some may contain black holes instead of neutron stars. The trick to learn is by measuring mass.

9.4 Origin of Gamma Ray Bursts

By far the most powerful bursts of energy we observe in the universe. Some appear to come from extremely powerful supernova explosions. A supernova from a neutron star does not release enough energy, however a supernova that forms a black hole (hypernova) might be powerful enough to explain it.

10 Summary Notes

- Observation evidence exists for white dwarfs and neutron stars, is strong for black holes
- All three can have close stellar companions in which they can accrete matter.
- Black holes are holes in the universe that strongly warp time and space around them. Nature of singularities beyond frontier of current understanding.

11 Chapter 14

11.1 Milky Way

11.1.1 Appearance

The Milky Way Galaxy has over 100 billion stars. It is a vast spiral galaxy consisting of spiral arms in a flat disc converging at a bugle in the center. The disc is surrounded by a dimmer halo (it is dimmer because most of the very bright stars are in the disc). The galaxy is 100 000 light years in diameter and 1000 light years thick. Our solar system is about 27 000 light years from the center.

It is difficult to view the galaxy because of clouds of interstellar gas and dust (called the interstellar medium) get in the way.

The Milky Way is one of the larger galaxies in our Local Group and its gravity influences smaller galaxies in the area. The Small and Large Magellanic Cloud galaxies actually orbit the Milky Way. Two even smaller and closer galaxies (Canis Major and Sagittarius Dwarf) are in the process of colliding with the Milky Way which will rip them apart.

11.1.2 Stars in Orbit

Stars in the disc of the galaxy orbit in roughly circular paths in the same direction and roughly the same plane. They orbit a bit like marry-go-rounds where the stars orbit the center but also bob up and down as they do. This bobbing happens because of localized gravity within the disc. When a star is to high the disk pulls it downwards, but it overshoots and becomes too low, repeat. The stars at the edge of the galaxy orbit at roughly the same speed as the stars at the center of the galaxy which is what gives it that swirl look.

Stars in the bulge and halo have randomly oriented orbits. Bulge stars move around the galactic center in elliptical paths with random orientations. Halo stars have much more exaggerated orbits, swooping high and low the disc at such high velocities that the disc's gravity barely effects them.

The Orbital Velocity Law:

$$M_r = \frac{r \times v^2}{G}$$

Where M_r is the amount of mass contained with this orbit (kg), r is the radius of the orbit(m), v is the object's orbital velocity (m/s) and G is the gravitational constant ($6.67 \times 10^{-11} \frac{m^3}{kg \times s^2}$).

11.2 Galactic Recycling

Interstellar mass is recycled within the galaxy's interstellar medium. This also changes the composition of the medium (stars make much heavier elements in their deaths).

11.2.1 Gas Recycling

- atomic hydrogen clouds - interstellar gas clouds fill the galactic disk
- molecular clouds - gas in the disk gradually cools and forms molecules
- star formation - gravity makes stars form molecular hydrogen mass
- nuclear fusion in stars - fusion in the cores of stars makes new elements from hydrogen
- hot bubbles - supernovae and stellar winds return gas and new elements to interstellar space
  - the strong solar winds from supernovae sweep surrounding material into a hot bubble, these continue to expand until the breach the galactic disk where they erupt, the erupted gas cools and rains back down onto the disk

  - supernovae also create shock waves that create walls of fast moving gas that heats and ionizes interstellar gas
- returning gas - returning gas cools and then blends into atomic hydrogen clouds
  - longest stage so its where most of the hydrogen lives
  - the matter rained down onto the disk cools and condenses into clouds (these may contain dust grains of carbon or silicon which are what blocks our view)
  - as the cloud cools hydrogen combine into molecules making it a molecular cloud
- repeat
  - in molecular clouds stars are formed
  - these stars' solar wind erode the clouds and keep more stars from forming
  - molecules fall apart and become ionized and join the near by atomic hydrogen clouds

Different parts of the Milky Way are at difference stages of the cycle so we can view the whole cycle via different wavelengths.

- radio emissions show atomic hydrogen (has a 21cm spectral line)
- radio emissions of carbon monoxide show the distribution of molecular clouds
- long-wavelength infrared emissions from interstellar dust show molecular clouds where stars are forming
- short-wavelength infrared emissions show the light from stars
- visible light shows how the galaxy looks and where dust blocks our view
- X-rays show where hot gas bubbles are
- gamma-rays show where gas densities are highest (most number of collisions) in molecular clouds

11.3 Location of Star Formation

Stars form in molecular clouds, duh. Locations where there are hot massive stars are indication of star birth places (those stars dont live very long). These areas also tend to be very colorful due to wisps of hot gas called ionized nebulae. These tend to be redder because electrons falling a level in hydrogen give off red photons. Nebulae that are bluer tend to be that color from dust grains reflecting light.

The spiral arms of our galaxy are full of new stars since they house many mollecular clouds and lots of young bright stars. Spiral arms form because molecular clouds collide quite often, these continue to compact until they become a birthing zone for stars.

11.4 History of the Milky Way

Unlike the disk that has stars of all ages, the halo has only old stars that contain fewer heavy elements. This is because the halo does not contain molecular clouds used for star formation so there can be no new stars in the halo and the halo is the oldest part of the galaxy before heavier elements existed as much.

Our galaxy started as a protogalacic cloud containing tones of hydrogen and helium. Gravity causes the cloud to contract and fragment. The bulge and halo stars formed first. At this point the galaxy was not disk shaped so these new stars orbited however they wanted. The gas continued to contract until it flattened into a disk due to the conservation of angular momentum. The concentrations of heavy elements in the halo stars implies that the Milky Way formed in multiple clouds that collided. Some halo stars move in organizes streams that implies that they came from other galaxies that collided with ours.

11.5 Galactic Center

The galactic center lies in the direction of Sagittarius. When we look at within 1000 light year of the center of our galaxy we see very dense cloud of gas and several million stars. At the center of this is the source a bright radio emissions, Sagittarius A*. Several hundred stars cluster Sagittarius A* within a light year and their orbital paths indicate a massive object at the center, about 4 million solar masses with a volume smaller than our solar system. This must be a black hole.

12 Chapter 15 – Galaxies and the Foundation of Modern Cosmology

By taking a picture of a small section of the sky and determining how many such pictures would be necessary to cover the entire sky, we can extrapolate that there are well over 100 billion galaxies within the observable universe. Each of these galaxies has a different shape, size, color, etc.

12.1 Types of Galaxies

We have three major categories of galaxies:

Spiral galaxies are flat white disks with yellowish bulges near the center. The disks are fileed with cool gas and dust, as well as some sparse ionized gasses, and usually have a few spiral arms. The Milky Way is a spiral galaxy.

Elliptic galaxies are redder, rounder, and tend toward being longer than they are wide. They contain less cool gas and dust than spiral galaxies and more of the hot ionized gasses.

Irregular galaxies appear lke neither of these categories.

The reason the galaxies are different colors is based on the relative ratios of stars of different colors within them: spiral and irregular galaxies are white-ish since they contain stars of all colors and ages, while elliptic galaxies are reddish since they are populated mostly by old and red stars.

We also categorize galaxies by size: dwarf galaxies contain as few as 100 million stars and giant galaxies contain more than 1 trillion.

12.1.1 Spiral Galaxies

Spiral galaxies have a thin disk which forms outwards from a central bulge. The disk smoothly merges into a dim halo with a radius which can be upwards of 100 thousand lightyears. The disk population [Population 1] (population of stars within the disk) includes stars of all masses and ages. The spheroidal population [Population 2] consists of halo and bulge stars, the halo stars being generally old and low in mass.

We thus define:

- The disk component is the flat disk in which stars follow orderly, nearly circular orbits around the galactic center. The disk component always contains an interstellar medium of gas and dust, but the amounts and proportions of molecular, atomic, and ionized gases in this medium differ from one spiral galaxy to the next.
- The bulge and halo together make up the spheroidal component, named for its rounded shape. Stars in the spheroidal component have orbits with many different inclinations, and the spheroidal component generally contains little cool gas and dust.

All spiral galaxies have both of these components, though some barred spiral galaxies have a straight bar of stars cutting through the center, with arms spiralling off of the ends of the bar. Lenticular galaxies are somewhat of a halfway between spiral galaxies and elliptical galaxies, as they have no spiral arms.

Approximately 75-85% of galaxies are spiral or lenticular.

12.1.2 Elliptical Galaxies

Elliptical galaxies have only a spherical component and no significant disk component. For this reason, they are sometimes called spheroidal galaxies. These galaxies tend to be small (and small elliptical galaxies are the most common of galaxies), though some are the most massive of galaxies: giant elliptical galaxies.

The composition of elliptical galaxies (ie. the ionized gasses) are much like the hot X-ray-producing gasses generated by supernovae and powerful stellar winds elsewhere in the universe.

Since these galaxies do not have many of the cool gasses found in other galaxies, they have very little ongoing star formation. This is why tese galaxies appear reddish: they tend to have very few young blue stars to counteract the color of the old red and yellow ones.

12.1.3 Irregular Galaxies

The irregular galaxies are all othre galaxies, which we can not easily classify. They are usually white and dusty and contain young massive stars. These also tend to be the oldest of galaxies: more irregular galaxies can be found the farther away we look. Though we aren't sure why, it seems that irregular galaxies were more common when the universe was younger.

12.1.4 Hubble's Galaxy Classes

Hubble designed a system for classifying galaxies: elliptical galaxies have a designation of E followed by a number from zero to seven, with a larger number signifying a larger eccenricity in shape: ie. an E0 galaxy is a sphere. Spiral and barred spiral galaxies have respective designations S and SB, followed by a lowercase letter from "a" to "c", where "c" corresponds to the smallest bulge and largest amount of dusty gas. Lenticular galaxies are designated S0 and irregulars are Irr.

12.2 Measuring Distance

We can measure the distance between the Earth and a galaxy using parallax. To do this, we must know the distance between the Earth and the Sun. This is done using radar ranging: by bouncing radio waves off of Venus and determining how long they take to return, we can find the distance to Venus. Keppler's laws, then, give us the distance to the Sun.

Since we can only measure within about a few hundred lightyears with parallax, we must also learn to measure distance by the inverse-square law of luminosity. Since similar stars should have similar luminosities (ie. a main-sequence G2 star like the Sun would have a similar luminosity), we can use the inverse-square law to determine how much farther it is from us than the Sun. For this approach, we must find standard candles: objects whose luminosity is known by which we can compare against.

Sun-like stars do not make very good candles since they are somewhat dim. To measure distances beyond a thousand lightyears, we need brighter candles. We thus have an approach by which we can get progressively better estimates: find a star within parallax distance, plot its HR, and establish luminosity from distance and brightness; then measure brightness of stars too far for parallax and use the inverse-square law to determine approximate distance.

Since we tend to use main-sequence stars for this, we refer to this technique as main-sequence fitting.

Unfortunately, this approach does not work well outside of our galaxy. We use brighter stars cepheid variable stars, or cepheids, for this task. These stars vary in brightness at some constant rate, from our perspective. The periods, though, are closely related to their luminosities: longer periods are found on more luminous stars. Cepheids, then, obey a period-luminosity relation which allows us to estimate their luminosity within 10% simply by measuring their period. A Cepheid with a period of 30 days is approximately ten thousand times brighter than the Sun.

Cepheids vary like this due to varying amounts of energy radiating from their surface: they have a peculiar problem in matching the amount of energy their surfaces radiate with the amount welling up from the core. The upper layers of a Cepheid variable star alternately expand and contract to attempt to find equilibrium, causing the stars luminosity to rise and fall. The periodluminosity relation holds because larger (more luminous) Cepheids take longer to pulsate in size.

We can use Cepheids as a stepping stone to find even brighter distant standard candles.

Some of the best distant standard candles are white dwarf supernovae, which are believed to be white dwarfs which have expanded beyond 1.4 times the mass of the Sun. Since these have a similar mass, these should all have comparable luminosities. Their luminosity is approximately ten billion times that of our Sun, and so we can detect them even in galaxies billions of lightyears away. The major disadvantage to this approach, of course, is that we can only measure the distance to galaxies with a supernovae-ing white dwarf; and this only happens once every few hundred years in the average galaxy. This technique, though, does allow us to calibrate an even better technique based on the expansion of the universe.

The spectra of most spiral galaxies tends to be redshifted; which occurs when a radiating object is moving away from us. When we measure the distance (using the above methods) as well as the redshifts of various galaxies, we notice that galaxies farther away from us are moving away at a faster rate. Thus, we determine that the universe is expanding. We express this with Hubble's Law

$$v = H_0 \times d$$

where v **is an object's velocity away from us and** H_0 **is Hubble's constant. Note that astronomer's tend to use this law in reverse: using a galaxy's speed to measure its distance away from us.**

Unfortunately, this is only an approximation, as the speed of a galaxy is impacted by the effects of gravity from nearby galaxies as well as from the expansion of the universe. In addition, we base our approximations upon how closely we can approximate Hubble's constant ($H_0 = 22\frac{km}{Mly \times s}$**).**

Note that the first of these issues impacts us most when measuring distances within the local group, as these are attracted to us by the Milky Way and thus move away from us at a much smaller rate than expansion would imply.

The major problem with measuring distances to galaxies is this chain of measurements; even today, based on the uncertainty at each step we can only be confident as

to a galaxy's distance within about ten percent.

Remember, this chain is:

1. Radar Ranging
2. Parallax
3. Main-sequence Fitting
4. Cepheid Variables
5. White Dwarf Supernovae
6. Hubble's Law

12.3 Age of the Universe

All our observations are consistent with the Cosmological Principle: that the universe appears identical at all locations. In other words, it has no "edge" or "center". More specifically, the universe is expanding – but it is not expanding *into* anything, nor is it expanding into nothing. It itself is an infinite, three-dimensional surface which has no edges, sides, or center.

The Hubble Constant, then, changes as the universe ages: at any given time $\frac{1}{H_0}$ is exactly equal to the age of the universe. Technically, the Hubble Constant is non-constant, then, but it varies slowly enough as to be virtually constant.

Based on our current estimate of Hubble's Constant, the universe is between 12 and 15 billion years old. To be more precise, we would need to know whether the rate of expansion is accelerating, which could change these values immensely: if the expansion rate has been increasing, the age of the universe woulld be somewhat more than $\frac{1}{H_0}$, and vice-versa. Our current best-estimate is that the universe is 14 billion years old.

12.3.1 Lookback Times

Since the universe is expanding, it can be difficult to refer to the distances to objects. If we see light from an object which left that object 400 million lightyears ago, then it is currently more than 400 million lightyears away. An object's lookback time is the difference between the current age of the universe and the age the universe was when light left that object. The lookback time of an object, then, is unambiguous.

The lookback time of an object is directly related to its redshift. This is because the expansion of our universe also stretches out the photons within it, thus giving us a cosmological redshift as well as a Doppler redshift. This is a difference in perspective, mostly, as we can either think of galaxies as hurtling through space or being carried along by the expanding universe.

The cosmological horizon represents the limits of the observable universe as a boundary in time, instead of space: in a universe 14 billion years old, we can not see any objects with lookback times greater than 24 billion years.

12.4 Evolution of Galaxies

We know far less about the life-cycles of galaxies than we do of stars. That said, we can use galaxies of various lookback times to view galaxies of different ages. We can not see far enough back to watch galaxies being formed, but we can determine their likely early life based on some assumptions:

- Hydrogen and Helium gas filled space uniformly soon after the birth of the universe
- The distribution of matter in the early universe was not perfectly uniform

We assume the denser areas grew into galaxies based on our understanding of the laws of physics. These regions of enhanced density would have expanded along with the rest of the universe, gradually slowing their expansion due to ever-increasing effects of gravity. Within a billion years, their expansion would have reversed, the material within them forming protogalactic clouds, which eventually formed galaxies.

The clouds which would eventually form spiral galaxies cooled as they contracted, and the first stars grew from the coldest, densest clumps of gas. These stars were likely massive, with lifespans of only a few million years. Their supernovae seeded these clouds with heavier elements and heated the surrounding gasses. This heating would have slowed the collapse of the clouds and their rate of star formation, allowing time for the gasses to form rotating disks.

This explains the shape of spiral galaxies: the spheroidal center consists of stars formed in the early stages, before a definite rotational plane was established, and thus have verying planes of rotation. Those formed on the arms were formed after a rotation had been established, and thus all follow the same plane.

This model, though, does not explain irregular and elliptical galaxies.

12.4.1 Variances in Galaxies

We attempt to determine why these galaxies differ by examining their differences: why do spiral galaxies have gas-rich disks, while other galaxies do not?

Two plausible explanations for the differences between spiral galaxies and elliptical galaxies trace a galaxys type back to the protogalactic cloud from which it formed:

Protogalactic Spin A galaxys type might be determined by the spin of the protogalactic cloud from which it formed. If the original cloud had a significant amount of angular momentum, it would have rotated quickly as it collapsed. The galaxy it produced would therefore have tended to form a disk, and the resulting galaxy would be a spiral. If the protogalactic cloud had little or no angular momentum, its gas might not have formed a disk at all, and the resulting galaxy would be elliptical.

Protogalactic Density A galaxys type might be determined by the density of the protogalactic cloud from which it formed. A protogalactic cloud with relatively high gas density would have radiated energy more effectively and cooled more quickly, thereby allowing more rapid star formation. If the star formation proceeded fast enough, all the gas could have been turned into stars before any of it had time to settle into a disk, making it an elliptical galaxy. In contrast, a lower-density cloud would have formed stars more slowly, leaving plenty of gas to form the disk of a spiral galaxy.

The second theory is consistent with observations: young elliptical galaxies tend to have very few young stars, implying their stars were all formed very quickly and that new star formation is not ongoing for long.

Another possible avenue for determining why galaxies differ is by looking at what changes after they are formed. Galaxies are not formed in isolation, and their interactions with other galaxies may be the cause of the differences.

Sometimes, galaxies may collide. These are immense interstellar events which cause enormous changes to the objects involved. These collisions were much more common in the early universe – back when galaxies were much closer together.

Based on computer simulations, we see that the collision of two spiral galaxies can form an elliptical galaxy since tremendous tidal forces rip the disks apart and a large fraction of the gasses sink to the center of teh collision and rapidly form new stars. Little of the disks remain in the end, and the stars have randomized orbits.

Elliptical galaxies are most common in areas of the universe with a large number of galaxies – which would be the case if they were often formed by the collision of other galaxies. Our observations tend to lend creedence to elliptical galaxies being formed this way. Elliptical galaxies tend to have structures corresponding to likely violent pasts and by observing central dominant galaxies we see that elliptical galaxies can grow to a large size by consuming other galaxies through galactic cannibalism.

Galactic collisions could also ignite huge bouts of star formation – starbursts – which can form entire starburst galaxies. Since these would consume al ltheir gasses extremely quickly, they would rapidly burst and emit galactic winds which carry away all gasses capable of supporting the constant star formation of a spiral galaxy.

12.5 Quasars and Other Active Galactic Nuclei

Some stars have extreme amounts of radiation and jets of material from their cores. These very crazy cores are called active galactic nulcei, the most luminous of these are called quasars. Quasars are only found at great distances wich tell us that they were much more common billions of years ago, from this we infer that quasar production decreases as galaxies age.

12.5.1 Quasars

The current theory is that the energy in a quasar comes from the accretion disk around supermassive black holes. Quasars were discovered when a scientist was mapping radio sources with visible objects and found a blue star that have emission lines that didnt appear to belong to any known chemical element. It was eventually found that these emission lines were just those of hydrogen that had been hugley redshifted. From there the objects distance and luminosity were calculated and shit was bright.

While quasars only appear very far away, we can find active galactic nuclei closer to home. Unfortunatly these suckers are small (only about 100 light years across) so it is very hard to resolve them. Using interferometry with radio images we have found that they are even smaller (less than 3 light years across) and the way they flicker implies they are even smaller.

Certain galaxies also emit unusually strong radio waves, called radio galaxies. These waves come from huge radio lobes on either side of the galaxy. At the center of the galaxy is a active galactic nuclei with two gigantic jets of plasma shooting into the radio lobes. Recent discoveries imply that radio galaxies and quasars are actually the same thing veiwed in different ways.

12.5.2 Power Source of Quasars and Active Galactic Nuclei

Currently we think that the energy of quasars and AGN comes from matter falling into black holes. The matter falling converts gravitational potential into kinetic energy and matter colliding on the way down converts that to thermal energy, and that resulting heat emits the crazy radiation we see.

This explains their crazy luminosities, how they emit radiation over a broad range of wavelengths, and their jets. Accretion disks convert 10-40% of mass into energy (much greater than a stars 1% conversion) which explains the high luminosities. Hot gas near the accretion disk emits ultraviolet and X-ray photons. This radiation ionizes near by interstellar gas which emits visible light (and the emission lines that led to their discovery). Dust grains in surrounding molecular clouds absorbe this light and emit infrared ratiation. The fast electrons in the jet emit radio radiation. The prescense of jets is harder to explain. We think its related to twisted magnetic fields caused by the spinning of the accretion disks.

12.5.3 Supermassive Black Holes

Some astronomers doubt the existence of supermassive black holes, and finding them is very difficult. By observing matter orbiting the centers of nearby galaxies we find that supermassive black holes are very common and possibly at the center of every galaxy. We do this by looking at the doppler shifts on either side of where we think the black hole is. If it is red on one side and blue on the other it means that gas is orbiting some unseen object. We can use mass and distance calculations to get the mass of the object at the center of this orbit. Many objects (molecular clouds in

particular) orbit very close to black holes (less than 1 light year), we can use this to guess the volume of it.

Black hole like objects appear in the center of a wide variety of galaxies with grossly different properties which implies that they are important to the formation of a galaxy, we just dont know how yet.

13 Chapter 16 – Dark Matter, Dark Energy, and the Fate of the Universe

The dominant source of gravity in the universe is dark matter, which is completely unobservable. bf Dark energy seems to be counteracting the effects of gravity on a massive scale.

In fact, the universe itself seems to be mostly composed of dark matter, rather than of atoms. Basically, dark matter is a theorized bunch of matter than may or may not exist but is necessary to create the effects our models predict. It is matter that gives off no light, ie. remains "dark".

We predict that the expansion of the universe must slow over time due to the diminishing effects of gravity. If it does not, there must exist some "dark" energy fueling the expansion. Note that sometimes we refer to dark energy as quintessence or a cosmological constant. There is also no real correlation between dark matter and dark energy, other than that we have determined their existance through their being *necessary.*

13.1 Evidence

We know that distance from the center of a circle and an object's orbital relation are related. It turns out if the center of the circle is the center of mass, the orbital speed decreases as we move away from the center. If the mass is distributed evenly, the orbital speed increases. Since the orbital speed of the stars within our galaxy increase as we move away from the galactic center, there must be a large amount of mass on the galaxy's halo. Since we can detect no radiation from it, we call that dark matter.

For galaxies that are not our own, we can make a similar calulation: using the mass-to-luminosty ratio, we can determine the total mass of the galaxy. Then, we can measure the velocities of stars and dust clouds in that galaxy and use the laws of galaxy to caluclate their mass. The difference in mass is dark matter.

We find that the composition of a spiral galaxy is typically 98% or more dark matter.

We can apply these same techniques to galactic clusters. If we assume they orbit each other, the gravitational calculations predict a far greater mass than their luminosities would. Thus we see that Galactic clusters are even more than 90% percent dark matter!

We can also measure the temperature of the hot gas (interstellar medium) within a galaxy by measuring the X-rays that medium emits. Since temperature is related to mass in this case, we can determine a galaxy's total mass with some calculations. Studies performed using this method see galaxies as containing more mass than luminosity would predict and thus agree with the above gravitational calculations.

We can also use **gravitational lensing to make the mass measurements. This technique relies on large masses "bending" light as it travels by exerting gravitational influences on the photons. By measuring the perceived shift, we can determine the mass of the objects between us and a source of light. By using this technique, we can use Einstein's Laws instead of Newton's. Since these results agree, we can increase our confidence in dark matter.**

We are pretty sure that there are two options:

- **our understanding of gravity is correct and dark matter exists, or**
- **our understanding of gravity is incorrect.**

That said, we are quite confident in our understanding of gravity. Furthermore, no one has been able to come up with an explanation which neatly explains our observations.

13.2 Composition

Dark matter may either be composed of particles we have already detected – but in some form as to be undetectable – or of exotic particles. At least most of it is likely exotic.

Dark matter could contain some non-exotic matter: if your body were in space, it would be undetectable as it would not be luminous enough to be visible. Similarly, planets, brown dwarfs, faint red M-sequence stars, etc are also classified as dark matter since they are too dim to be seen. That siad, if dark matter contained any of these objects, we could detect it: due to gravitational lensing, any of these objects passing in front of any source of light would be noticeable. The duration of this lensing would reveal the object's mass. We have discovered a few of these events, but not nearly enough to explain dark matter's prevalance or mass. Similar measurements agree dark matter can not be mostly comprised of black holes.

Models of nuclear fusion give us an estimate of the total number of protons, neutrons, etc in the galaxy. Their mass would comprise about one-sixth of the measured mass of the universe; thus there must be some exotic particles filling the five-sixths of the universe's mass.

We imagine dark matter to be composed heavily of weakly interacting massive particles, or WIMPs. These particles would be similar to neutrinos, in that they interact only with a couple of the four forces (ie. weakly interact) but far more massive and slower moving. Note that though these are refered to ass "massive particles", they are really subparticles and are thus only massive relatively speaking.

A large amount of WIMPs being present in the outer halo of a galaxy fits within our current understanding.

We have not yet detected any WIMPs, but through large-scale space particle detection and particle colliders, we are hopeful we will detect some soon.

13.3 Dark Matter's Role

Dark matter likely played an essential role in formating galaxies: by being os large in mass, areas high in dark matter likely attracted many other particles and eventually developed the mass to become a galaxy.

We also know that the universe is arranged into galactic clusters, superclusters, and even large sheets of superclusters. The reason mass in our universe is so highly divided is likely due to the effects of gravity from large amounts of dark matter. In fact, the current galactic structure likely mirrors the initial distribution of dark matter.

13.4 The Fate of the Universe

We can determine a critical density of our universe by which a universe with a larger density will eventually start contracting and one with a smaller density will simply expand forever. Including dark matter, our estimates of the universe's matter content fall short of this critical density (we measure mass approximately equal to 0.5% of the required amount and believe dark matter is 50 times more massive, thus we have 25% of the required mass). Thus the universe seems likel to continue expanding forever, as we are doubtful there is more dark matter than we have predicted.

In fact, the expansion of the universe is *increasing over time, which should not happen based on our understanding of gravity. Thus we label dark energy as the force causing the expansion.*

13.4.1 Expansion Patterns

Given future changes in expansion rates, we determine four possible expansion patterns:

recolapsing *if there were no dark energy and the universe was above critical density, universal expansion would eventually reverse and end in a "big crunch". This is sometimes refered to as a* closed universe, since it could be modelled by a mathematically closed sphere in more dimensions.

critical if there were no dark energy and the universe was at critical density, the universe's expansion would slow over time but never reverse. Mathematicall, we could call this a flat universe.

coasting if there were no dark energy and the universe was below critical density, the universe would keep expanding at its current rate forever. We could mathematically call this an open universe.

accelerating if dark matter exerts a repulsive force which causes the universe's expansion to acclerate over time, the universal expansion rate would increase over time. This type of universe may be closed, open, or flat. Current evidence points to our universe being an accelerating flat universe.

Based on the average distance between galaxies over time, we seem to be in an accelerating universe. We measure this by looking at white dwarf supernovae: their distance tells us the lookback time and their redshift tells us what rate the galaxy had been expanding at.

14 Chapter 17: The Beginning of Time

14.1 The Big Bang

We can use light from distant galaxies to see about a billion years into the past, beyond this we cannot see any objects bright enough. We also run into a problem with background radiation left over from the Big Bang. This radiation is from when the universe was 380 000 years old (before that light could not pass through). Most of our knowledge of the Big Bang is from mathematical models.

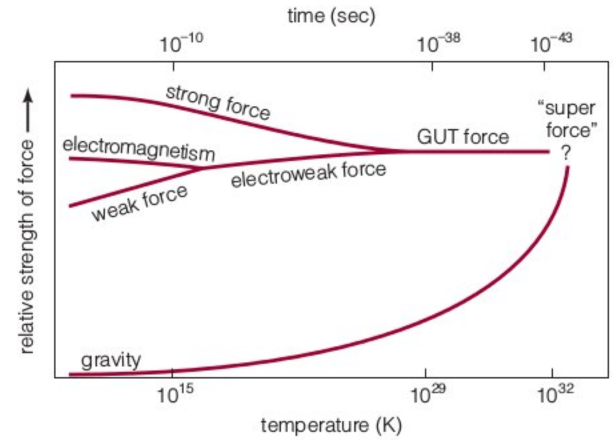
14.1.1 Conditions of the Early Universe

During the first few seconds the universe was so hot that photons could transform themselves into matter and back. When two photons collide with energy twice that of a electron (its mass times c^2*) they make a electron (matter) and positron (antimatter). When these two meet they annihilate each other and release photon energy. Similar actions can be done for protons and neutrons. At its start, the universe was full of matter and antimatter jumping to and from energy.*

Forces:

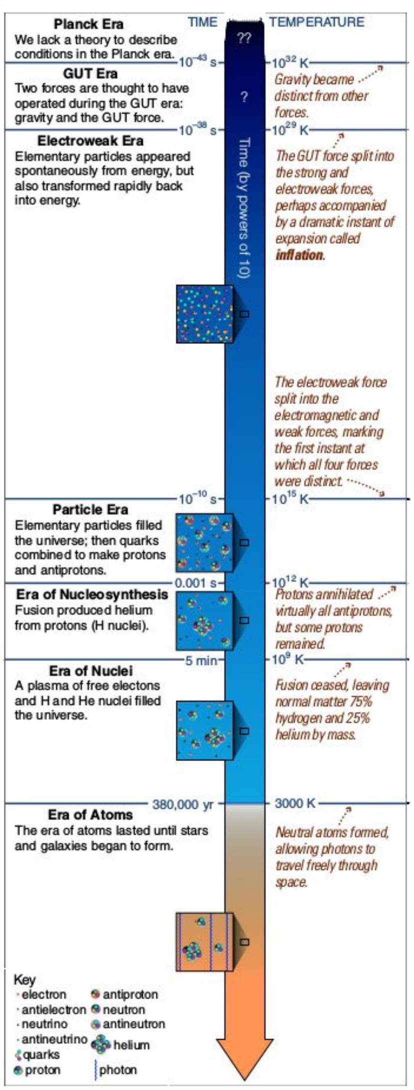
- *Gravity: holds planets together (dominant on large objects)*
- *Electromagnetism: holds particles together (dominant on atoms and molecules)*
- *Strong nuclear: holds atom nucleus together*
- *Weak nuclear: deals with fusion and fission*

At high temperatures (like at the birth of the universe) some of these meld into a different force. At its very start the universe was governed by one super force.



14.1.2 History of the Universe

We break the history of the universe into eras.



Planck Era *This is the limit of what our current understanding of physics can explain. At this point we know that mass and energy were being converted back and forth rapidly. These energy fluctuations caused a changing gravitational field that warped space and time. A problem arises in that we have no theory to link quantum mechanics and general relativity. This era ended when the universe cooled enough for the super force to break into GUT force and gravity.*

GUT Era *We know barely more about this era than we do about the Planck era, and even then what we know is not well tested. We think that the separation of GUT into strong and electroweak forces released a ton of energy causing a dramatic expansion of the universe called* ***inflation*** *(we think expanding things of atomic size to solar system sized).*

Electroweak Era *At the end of this era the electroweak force breaks apart into the electromagentic and weak nuclear forces. This is the first point where we have experimental evidence of things actually fitting our models. Particle accelerators produced weak bosons that we predicted would exist during this era.*

Particle Era *This is the era right before the crazy energy-particle switching calmed down. All of the quarks created during this era had combined into protons and neutrons by its end. Since we were not spontaneously making matter and antimatter the two started permanently annihilating each other. We know that matter out numbered antimatter because matter exists. By comparing estimates on how many protons and photons there are we can get a rough estimate of the size of matter antimatter imbalance. The two numbers would have been similar at the start of the universe,* *but now photons outnumber protons a billion to one. This means that for every billion antiprotons there were a billion and one protons so when the billion annihilated themselves they made a billion extra photons.*

Era of Nucleosynthesis *Now that we had a steady amount of matter it started fusing into heavier elements but the heat of the universe kept breaking them apart. At the end of this era it had gotten too cool to fuse heavier elements.*

Era of Nucleus *At this point the universe consisted of plasma made of hydrogen and helium nuclei and electrons. Light didnt really go anywhere because it just bounced around between electrons (like it does inside a star). At the end of this era the universe had cooled enough for the nuclei to snag electrons and become stable. Once that happened light could travel in straight lines.*

Era of Atoms and Era of Galaxies *Now that we have stable atoms we can be in the era of atoms. The universe is now a mix of neutral atoms, plasma, and photons. Slight areas of higher density started attracting atoms and plasma to make protogalactic clouds. These went on to form stars and eventually galaxies. This is the era we are currently in.*

14.2 Evidence

The big bang theory is widely accepted because it accurately predicts ***cosmic background microwave radiation*** *as the radiation that started streaming through the universe at the end of the nuclei era. It also accurately predicts the amount of helium in the universe.*

14.2.1 Left Over Radiation

Arno Penzias and Robert Wilson kept hearing noise on their microwave antenna, this was background radiation from the universes formation. They found that the noise was exactly the same from every direction (so it wasn't just coming from something). At the same time a group at Princton had found that the radiation created during the formation of the universe (predicted by George Gamow) would have to still exist and be detectable with microwave antennas.

Scientists predicted that cosmic background radiation would have a prefect thermal spectrum since it was from the start of the universe. Since it broke free when the universe was the temperature of a red giant it should have the same signature, but stretched by 1000 (since thats how much the universe has expanded since then). This shifted spectrum represents the temperature just above absolute 0. The Cosmic Background Explorer (COBE) satellite was launched to test these theories and it confirmed that cosmic background radiation has a perfect thermal spectrum and is about 3K. COBE also showed that background radiation is not absolutely the same in every direction. This had been a strike against the Big Bang Theory since the universe couldn't have been that smooth (it had to have pockets of slightly higher gravity for starts to form).

14.2.2 Abundance of Elements

Background radiation also explains a discrepancy in the amount of helium in a galaxy. No galaxy is $<$ 25% helium, but star fusion can only produce 10% helium. This means that some helium must have been present during the formation of the universe, so the universe must have been hot enough at some point to fuse hydrogen. The temperature of the background radiation can be used to calculate how hot the universe was in the past and this can be used to calculate how much helium was fused (roughly 25%).

During the formation of the universe it was hot enough to switch between protons and neutrons, but as it cooled the universe favored creating protons since neutrons are heavier. During this time protons and neutrons combined to form deuterium (weird hydrogen nucleus containing a neutron). Deuterium fused to form helium. Most of these were blown apart by gamma radiation but as the universe continued to cool some stuck around. Here protons outnumbered neutrons seven to one. All neutrons were incorporated into helium-4 atoms resulting in one helium (weight 4) for every 12 hydrogen (weight 1 each), so 25% of the universe's weight was helium.

Rarely reactions could form lithium, but all other elements were created in stars. This is because by the time the universe has stable helium and hydrogen atoms to fuse into heavier elements it was too cool to fuse them.

14.3 Inflation

Lots of what we know about the origin of the universe is uncertain because we have no way to experimentally verify them.

14.3.1 Mysteries

Stuff we cannot explain with the Big Bang Theory without inflation:

- *the structure: matter collected around areas of slightly higher density, where did these come from and why were they there*
  - *we can experimentally prove that the energy fields at any point in space fluctuate slightly, these might cause density enhancements*
  - *inflation would have increased the wavelengths of these fluctuations to be large enough to generate the density enhancements that existed (based on background radiation calculations)*
- *the uniformness: for something of its scale the universe is surprisingly smooth (varying by only 0.01%)*
  - *before inflation radiation was continuously bouncing around and interacting which lead to a normalization of it*
  - *inflation then flung this radiation far apart from each other very quickly so that they didn't have time to fuck with each other resulting in the smoothness we see*

- *density id close to critical density: if we sum dark matter and dark energy we find that the universe density is far too close to the critical density to be a coincidence*
  - *the universe is surprisingly flat which is only possible if its density was uniformly equal to the critical density (point at which kinetic expansion matched gravitational pull)*
  - *inflation explains this by expanding the universe so quickly that any curvature would not be noticeable on the scale of our universe*

Note: inflation does not violate the speed of light since things aren't moving through a distance quickly, the distance itself is stretching.

14.3.2 Testing Inflation

We test inflation by using it to make predictions and seeing if its right (and it is);

- *The overall geometry is flat, implying that the total mass-energy of the universe is equivalent to the critical density.*
- *The density of ordinary matter is 4.6% of the critical density, in agreement with observations of deuterium in the universe.*
- *The total matter density is 28% of the critical density. Subtracting the 4.6% for ordinary matter, we conclude that dark matter, probably in the form of weakly interacting massive particles, makes up about 23% of the critical density, in agreement with what we infer from measurements of the masses of clusters of galaxies.*
- *The combination of a flat geometry and a matter density lower than the critical density implies the existence of a repulsive force due to dark energy that currently accelerates the expansion, in agreement with observations of distant supernovae. Because the total mass-energy of the universe is the critical density, and matter accounts for only 28% of this, dark energy must account for the remaining 72% of the mass-energy of the universe.*
- *The universes age should be about 13.7 billion years at the current microwave temperature of 2.73 K, in agreement with what we infer from Hubbles constant and the ages of the oldest stars.*

14.4 Observing the Big Bang

They sky is dark at night. Duh. But this actually makes no sense. ***Olber's Paradox*** *is that if the universe is infinite and unchanging, then the sky should be as bright as the sun. Since the universe is infinite in every direction, there should be almost no part of the sky that doesn't have a source of light in the way. Even with the explanation of dust and black holes, the sky is too dark. The Big Bang Theory explains this by saying we can only see a finite number of stars because the universe began at a particular moment so our field of vision is limited.*

15 Chapter 18 – Life in the Universe

- *Reasons why life likely might exist elsewhere*
  - *Life arose quite quickly on Earth, so why not on other planets too*
  - *Chemicals on young Earth combined readily into complex organic compounds. This may also be true on other exoplanets.*
  - *We have discovered microorganisms that could survive on other planets in our solar system*
- *Timeline of development of life on Earth:*

Years ago	*Event*
4.5 billion	*Earth and moon form*
3.85 billion	*Carbon isotope evidence of life*
3.5 billion	*Oldest microfossil evidence of life*
2.5 billion	*earliest evidence of oxygen in the atmosphere*
410 million	*animals colonize land*
230 million	*mammals and dinosaurs appear*

- *Requirements for life (on Earth)*
  - *A source of nutrients*
  - *Energy to fuel the activities of life*
  - *Liquid water (* this is the only one that is difficult to achieve)*
- *Microbes living in extreme conditions (volcanic vents, deserts) imply that if not for a need for water life could exist almost anywhere*
- *Only likely candidates to have liquid water in our solar system are Mars and some jovian moons (e.g. Europa)*
- *What properties must a star system have to contain life*
  - *It must be older than several million years (that's how long life took to form after Earth's formation)*
  - *The star must not be much bigger than our Sun, because it would die off before life formed (still leaves about 99% of stars)*
  - *Planets must have stable orbits (far less likely in binary star systems, but not impossible)*
  - *Bigger star means larger habitable zone (the zone where liquid water could exist)*
- *A planet's spectra can give us the atmospheric makeup, allows us to look for water vapour, ozone, methane, etc.*
- *Rare-Earth hypothesis*
  - *The galaxy has a habitable zone, just like our solar system*
  - *Star systems further out contain far less non-hydrogen/helium elements, which almost completely compose terrestrial planets*

- *Inner systems are subject to far more high supernovae, which would likely irradiate life*
- *Leaves only about 10% of solar systems habitable*
- *Impact rate in our solar system dropped off quickly, is the same true everywhere? In our solar system this was due to jovian planets ejecting small objects from the inner solar system*
- *Our atmosphere has been relatively stable due to plate tectonics (which might be rare on other planets) regulating the carbon dioxide, and our large moon regulates our axial tilt*

- *Counter-arguments include*
  - *Earth is very small and wouldn't need a high abundance of heavy elements to form (relative to the mass of the star)*
  - *We don't know if a supernova would be harmful to life*
  - *If the Earth rotated faster it would also regulate our axial tilt without the Moon*
  - *Large moons could exist other places, ours isn't that rare*
  - *Life could adapt to a changing axial tilt*
- *Drake equation: Number of civilizations* $= N_{HP} * f_{life} * f_{civ} * f_{now}$

  $N_{\mathbf{HP}}$ *number of habitable planets in the galaxy that* could *have life*

  $f_{\mathbf{life}}$ *fraction of habitable planets that actually have life*

  $f_{\mathbf{civ}}$ *fraction of life-bearing planets upon which a civilization capable of interstellar communication* has at some time *arisen*

  $f_{\mathbf{now}}$ *fraction of civilization-bearing planets that currently have such a civilization*
- *Fermi paradox: If it's so likely that other civilizations exist than there are some millions of years ahead of us technologically. So where are they? Options: "we're alone", "every other civilization destroyed itself before it could settle the galaxy" or "they haven't revealed themselves to us yet"*

16 Assignments

16.1 Assignment 1

Distance from Earth *(furthest to closest): Andromeda, far side of the milky way, near side of the milky way, orion nebula, Alpha Centauri, Pluto, The Sun*

If an object is 10 light-years away, then we see it as it was 10 years ago, but if it is 20 light-years away, we see it as it was 20 years ago. In other words, more distant objects have aged more since their light left on its way to Earth.

Timeline: Universe begins to expand, Elements such as carbon and Oxygen first form, nuclear fusion begins in the Sun, Earliest life on Earth

Our cosmic address: Earth, solar system, Milky Way Galaxy, Local Group, Local Supercluster, universe

We cannot See a Universe that is 20 billion years away because it is not in our observable universe

16.2 Assignment 2

The **Tilt of a planet is responsible for seasons**. *Jupiter (3*) has almost no seasons compared to Uranus (97*). Earth and Mars have a similar tilt.*

Time of Year	*Earth-Sun Distance*
March (Northern Spring Equinox)	*149.0 million km*
June (Northern Summer Solstice)	*152.0 million km*
September (Northern Fall Equinox	*150.2 million km*
December (Northern Winter Solstice)	*147.2 million km*

Earth is actually farthest from the Sun when it is summer in the Northern Hemisphere. We conclude that variations in the Earth-Sun distance from are not the major cause of our seasons.

The **Moons orbit about Earth is tilted** *(by about 5) with respect to Earths orbit about the Sun. As a result, the actual number of solar eclipses that occur each year is approximately 2 (instead of one each month)*

Apparent **retrograde motion can be observed by noticing changes in Mars's position among the constellations**. *Note that a complete period of apparent retrograde motion unfolds while Earth moves a significant fraction of its orbit, which means it takes several months. Apparent retrograde motion occurs as Earth "laps" Mars in their respective orbits around the Sun. The middle of a period of apparent retrograde motion occurs when Mars is closest to Earth in its orbit and in a full phase as viewed from Earth, which is why it is brightest in our sky at that time. It is also directly opposite the Sun in the sky at that time, which is why it crosses the meridian at midnight.*

The **Greeks explained retrograde motion by imagining that planets moved around small circles that in turn moved around larger circles around Earth**. *Because this model made reasonably accurate predictions of planetary positions and fit with other philosophical ideas that they held, the Greeks had no compelling reason to reject it,*

Random: *How frequently does the Galactic Center (in the constellation Sagittarius) and the Sun align, that is, appear in the same constellation? Once A year*

Neutrinos rarely interact with anything on Earth (faulty premise of movie 2012)

16.3 Assignment 3

Kepler's second *law tells us that as an object moves around its orbit, it sweeps out equal areas in equal times*

Venus *is full whenever it is on the opposite side of the Sun from Earth, although we cannot see the full Venus because it is close to the Sun in the sky. For Venus to be high in the sky at midnight,* *it would have to be on the opposite side of our sky from the Sun. But that never occurs, because Venus is closer than Earth to the Sun.*

Falsifiable*: (could be proven false)*

True Statements belong in Sun centered and "Both" models

Earth Centered Model Only

- *A planet beyond Saturn rises in east and sets in West*

Sun Centered Only

- *Positions of nearby stars shift back and forth slightly each year*
- *Mercury goes thorough a full cycle of phases*

Both Models

- *Moon rises in east and sets in west*
- *A distant galaxy rises in the east and sets in the west*
- *stars circle daily around north and south celestial pole*

Neither Model

- *We sometimes see a crescent Jupiter*

An object must come between Earth and the Sun for us to see it in a crescent phase, which is why we see crescents only for Mercury, Venus, and the Moon.

Greek geocentric model*, the retrograde motion of a planet occurs when the planet actually goes* **backward in its orbit around Earth**

Random: *Copernicus's Sun-centered model did not make significantly better predictions of planetary positions in our sky. (not an advantage of it)*

Tides:

- *Any particular location on Earth has two high tides and two low tides each day.*
- *Tides also affect land, although not as much*
- *One tide bulge faces the moon, the other is away from*
- *The second tidal bulge arises because gravity weakens with distance, essentially stretching Earth along the Earth-Moon line.*
- *High tides are highest at both full moon and new moon*
- *Low tides are lowest at both full moon and new moon.*
- *Moon is larger factor than the sun because gravitational attraction between Earth and the Moon varies more across Earth than does the gravitational attraction between Earth and the Sun*

16.4 Assignment 4

- *The Sun emits all colors of visible light, but cooler gasses on the Sun's surface absorb some of these colors.*
- *The most intense color in an absorption spectrum can tell us the temperature of an object.*
- **Wien's Law***: thermal radiation from a higher object peaks at a shorter wavelength.*
- *Electrons lose energy exactly equal to the proportion of distance between "rings" they jump, regardless of which rings they traverse.*
- *Visible light and radio waves reach the Earth's surface, infrared light reaches mountain tops, UV light reaches the upper atmosphere, and X-rays don't enter the atmosphere.*
- *The light-carrying area of a telescope varies at a rate double its diameter.*
- *The Hubble Telescope has a resolution of less than 0.1 arcseconds.*

16.5 Assignment 5

Jovian planets __________ *than terrestrial planets:*

- *Are more massive*
- *Are lower in average density*
- *Are bigger*
- *Orbit the Sun farther*
- *Have more moons*
- *Have rings*

How are Pluto and Eris different from other planets:

- *Smaller*
- *More elliptical orbits*
- *Less massive*
- *Similar composition to comets (ice and rock)*

Characteristics of planets in our solar system:

- *Large bodies have orderly motions*
- *There are exceptions to most trends*
  - *Venus spins backwards*
  - *Uranus rotates on its side (axial tilt* $\approx 90°$*)*
  - *The moon is about* $\frac{1}{4}$ *the size of Earth*
- *Planets orbit the Sun in the same plane*

- *Planets closer to the Sun move around their orbits at higher speed than planets farther from the Sun*
- *All the planet (not counting Pluto) have nearly circular orbits*

Small bodies:

- *Rocky = asteroids*
  - *Found in the asteroid belt*
- *Icy = comets*
  - *Found in the Kuiper belt (starts around Neptune, extends past Pluto) and Oort cloud (sphere around the solar system, far beyond Pluto)*

Detecting extrasolar planets

- *Planets are very dim compared to their star, it makes it very hard to image them visually. The angular separation from Earth is also very small.*
- *We can detect planets by watching how their star "wobbles" due to their gravity (Doppler technique). This technique can only give us the* ***minimum*** *mass of the planet (unless it's on the same plane as the Earth)*
- *Smaller orbital radius of planet results in higher max speed of the star and shorter period of rotation*
- *Mass of the planets only affects the max speed of the star in its "wobble"*
- *If the planets orbital plane lie between the Earth and the star we can see eclipses — a slight dip in the stars luminosity*
- *As of 2008, the most extrasolar planets have been discovered by the Doppler technique*
- *The Kepler mission mostly looked for eclipses*
- *Transit technique has the best chance of finding Earth-like planets*
- *The astrometric technique uses careful measurements of positions of celestial bodies to find planets*

Properties of extrasolar planets (discovered so far):

- *Some jovian planets have been found closer to their star than Mercury is to the Sun (hot Jupiters)*
- *Many are on very eccentric orbits*
- *Jovian planets migrate closer to their star from their original orbits*
- *Most are larger than Jupiter*

Four process that shape planetary surfaces:

- *Impact cratering*
  - *number of impacts per square area about the same for all planets*

- *Mostly occurs in the first few hundred million years after formation*
- *Primary factor for craters still being visible is if they've been erased, because they were definitely there at some point*

- *Volcanism*
  - *Outgassing explains how terrestrial planets got their atmospheres*
- *Tectonics*
  - *Happens beneath the* lithosphere*, the rigid layer of rock at the surface of a planet*
  - *Compression causes mountain ranges*
  - *Extension (stretching) causes cracks and valleys*
  - *Earth is the only planet where the lithosphere has been broken into plates*
  - *Lots of tectonic activity means lots of volcanic activity*
  - *Can only occur if the interior of the planet is liquid (hot!)*
  - *Big planets take longer to cool than small ones, so they have tectonic activity for longer*
- *Erosion*
  - *Occurs due to surface liquids, ices and gases*
  - *Liquid water is the best, causes much more pronounced features*
  - *Canyons (formed by glaciers), dunes, rock formations*
  - *Planet must be warm enough to have liquids, and big enough to capture an atmosphere*

17 Assignment 9

Stages of birth of a star from first to last:
molecular cloud fragment, contracting cloud trapping infared light, protostar with jets, main-sequence star

From Highest to lowest temp:
main-sequence star, protostar with jets, contracting cloud trapping infared light, molecular cloud fragment

Fastest to slowest:
main-sequence star, protostar with jets, contracting cloud trapping infared light, molecular cloud fragment

Newly forming star has the greatest luminosity when it is a shrinking protostar with no internal fusion. Greatest energy source at this luminosity is gravitational contraction

Most of the gas remaining from the process of star formation is swept into interstellar space by a **protostellar wind.**

Planets may form within the protostellar disk that surrounds a forming star.

Main-sequence Phase

- **lasts about 10 billion years**
- **surface radiates energy at the same rate that core generates energy**
- **energy generated by nuclear fusion**

Protostar Phase

- **pressure and gravity not precisely balanced**
- **energy generated by gravitational contraction**
- **luminosity much greater than the sun**
- **radius much larger than the sun**

interstellar medium: the gas and dust that lies in between the stars in the Milky Way galaxy

Interstellar clouds called molecular clouds are the cool clouds in which stars form.

Most abundant in an interstellar molecular cloud: H_2.

Interstellar dust consists mostly of microscopic particles of carbon and silicon.

Part of electromagnetic spectrum generally giving best views of stars forming in dusty clouds: infared.

Looking by eye at a star near the edge of a dusty interstellar cloud. The star will look dimmer and redder than it would if it were outside the cloud.

Most interstellar clouds remain stable in size because the force of gravity is opposed by thermal pressure within the cloud.

A cold, dense gas cloud is most likely to give birth to star because this type of cloud has lower thermal pressure (due to the low temperature) and stronger gravity (due to the high density).

Core temperature required before hydrogen fusion can begin in a star: 10 million K

Smaller stars spend more time in the protostellar phase of life

Vast majority of stars in a newly formed star cluster are less massive than the Sun

Brown Dwarfs:

- **form like ordinary stars but are too small to sustain nuclear fusion in their cores**
- **have masses less than about 8% that of our Sun**
- **supported against gravity by degeneracy pressure, which does not depend on the object's temperature**

Radiation pressure prevents stars of extremely large mass from forming

Stages of a high mass star (first to last):
contracting cloud of gas and dust, protostar, main-sequence O Star, red supergiant, supernova, neutron star

Elements from first to last produced:
Helium, Carbon, Oxygen, Iron

The CNO Cycle is the process by which hydrogen fusion proceeds in high-mass stars.

If you returned to our solar system in 10 billion years you would most likely see a white dwarf

High Mass Stars ($> 8M_Sun$):

- **have higher fusion rate during main sequence life**
- **late in life fuse carbon into heavier elements**
- **end in a supernova**

Low Mass Stars ($< 2M_Sun$):

- **final form is a white dwarf**
- **have longer lifetimes**
- **end life as a planetary nebula**

The core of a high-mass star shrinks and heats up after it runs out of hydrogen.

17.1 Assignment 11

The Cosmic Distance ScaleCepheids

- **Cepheids with longer periods have higher luminosities**
- **How to use Cephids to measure distance:**
  - **Step 1: Measure the period of the Cepheid's brightness variations.**
  - **Step 2: Use the period-luminosity relation to determine the Cepheid's luminosity.**
  - **Step 3: Calculate the Cepheid's distance from its luminosity and apparent brightness.**

The Cosmic Distance ScaleFrom the Solar System to the Universe

- **What baseline distance must we know before we can measure parallax?**
  - **the Earth-Sun distance**
- **Standard candle techniques**
  - **white dwarf supernovae (distant standards)**
  - **Cepheids**

  - main-sequence fitting

The Cosmic Distance ScaleHubble's Law

- Hubble's law expresses a relationship between the distance of a galaxy and the speed at which it is moving away from us
- But before we can use Hubble's law, we must first calibrate it by measuring the distances to many distant galaxies with a standard candle technique
- meaning of Hubble's constant: It describes the expansion rate of the universe, with higher values meaning more rapid expansion

Understanding Hubbles Law

- Hubbles law tells us that the more distant a galaxy is from Earth, the faster it is moving away from us
- more distant galaxies move at higher speeds
- a steeper slope (distance vs speed) for Hubbles law would predict faster speeds for galaxies at particular distances

Visual Activity: A Graph of Hubbles Law

- galaxies with high speeds as measured from Earth are moving away from Earth and are farther from Earth than galaxies with lower speeds
- galaxies that have the lowest speeds are moving away from Earth and are closer to Earth than galaxies with high speeds
- galaxy B is twice as far from Earth as galaxy A. Hubbles law predicts that galaxy B will be moving away from Earth with approximately twice the velocity of galaxy A
- he slope of Hubbles law on the graph is actually steeper than that shown. In that case, the age of the universe would be younger than 14 billion years because the universe is expanding more rapidly than current data suggest

Which of these galaxies would you most likely find at the center of a large cluster of galaxies? a large elliptical galaxy

In which of these galaxies would you be least likely to find an ionization nebula? a large elliptical galaxy

If all the stars on the main sequence of a star cluster are typically only one-hundredth as bright as their main-sequence counterparts in the Hyades Cluster, then that cluster's distance is 10 times as far as the Hyades's distance.

Which of these galaxies is most likely to be oldest? a galaxy in the Local Group

About how many galaxies are there in a typical cluster of galaxies? a few hundred

When the ultraviolet light from hot stars in very distant galaxies finally reaches us, it arrives at Earth in the form of visible light.

Why do virtually all the galaxies in the universe appear to be moving away from our own? Observers in all galaxies observe a similar phenomenon because of the universe's expansion.

If you observed the redshifts of galaxies at a given distance to be twice as large as they are now, then you would determine a value for Hubble's constant that is twice as large as its current value.

Redshift of value z: $1 + z = \frac{\lambda_{obsv}}{\lambda_{emit}} = \frac{d_{now}}{d_{past}}$ **where obsv is wavelength observed and emit is wavelength emitted and d is distance.**

Galaxy FormationSpiral or Elliptical

- **A collision strips gas out of a spiral galaxy, this tend to change the spiral galaxy into an elliptical galaxy because a galaxy cannot have a disk if it does not have gas**
- **High density tends to lead to more rapid star formation in a protogalactic cloud which leads to an elliptical galaxy, rather than a spiral galaxy because rapid star formation means that there may not be enough gas left to make a disk.**
- **High angular momentum leads to faster rotation which leads to a spiral galaxy, rather than an elliptical galaxy because faster rotation leads to collisions among gas particles that cause the gas to settle into a spinning disk, rather than a more spread out cloud.**

Which of these items is a key assumption in our most successful models for galaxy formation? Some regions of the universe were slightly denser than others.

A collision between two large spiral galaxies is likely to produce a large elliptical galaxy.

The luminosity of a quasar is generated in a region the size of the solar system.

The primary source of a quasar's energy is gravitational potential energy.

Supermassive black holes found at the centers of galaxies are related to the properties of those galaxies in which of the following ways? The mass of the black hole is related to the mass of the galaxys bulge.

A collision and merger of two large elliptical galaxies will eventually produce a large elliptical galaxy.

Starburst galaxies are especially bright in infrared light.

The rate at which supernovae explode in a starburst galaxy that is forming stars 10 times faster than the Milky Way is about 10 times higher than in the Milky Way.

18 Assignment 12

18.1 Dark matter

- **Effects the orbits of stars and gas, causing faster motion than we can account for**
- **Stellar masses only account for most of the total mass close to the center of a galaxy**
- **total mass - luminous mass - mass of hot gas = dark matter**
- **Two main options**
  - **Ordinary - made of protons, neutrons, electrons. Simply can't be detected**
  - **Extraordinary - weakly interacting massive particles (WIMPs). Mysterious netruino-like particles. This is the best bet**
- **There isn't enough ordinary matter to explain ordinary dark matter**
- **Evidence:**
  - **Masses measured for galaxy motions**
  - **Temperature of hot gas (can be used to determine mass of galaxy)**
  - **Gravitational lensing**
- **WIMPs can't collapse because they don't radiate away their energy. They helped protogalactic clouds collapse without collapsing themselves**
- **Dark matter lumps the universe together; accounting for expansion, galaxies are being drawn together into chains and sheet.**

A rotation curve is a plot showing orbital speed versus distance form the center.

- **Rigid disk = proportional**
- **Solar system = decreasing exponential**
- **spiral galaxy = increases as you move away from the center then levels off**

Rotation curves show us that instead of velocity decreasing as you move away from the center of a galaxy, it increases, or remains constant. Both indicate that more mass is contained within the orbit than we would expect

- $v = \sqrt{\frac{M_r * G}{r}}$
- M_r **= encircled mass**
- r **= radius of sphere containing the mass**

Definitions

WIMPS: subatomic particles that have more mass than neutrinos but do not interact with light
Baryonic matter: Matter made from ordinary atoms
Gravitational lensing: The effect made when a massive object distorts the light coming from objects behind it

18.2 Dark Energy

Galaxies are expanding at an ever-increasing rate. This is impossible if gravity is the only force involved as it would cause the speed of galaxies to decrease.

The energy causing this repulsion is called dark energy.

Critical density: The average density of the universe such that:
density $<$ critical density $\Rightarrow$ the universe expands at an ever decreasing rate, but never stops.
density $>$ critical density $\Rightarrow$ the universe stops expanding the collapses.

If a critical universe has an average density of one, our universe is ≈ 0.3. So it should be coasting.

Dark energy makes it so that instead of the rate of expansion slowing, it is actually increasing. This also gives us the oldest model of the universe.

The is the age of the universe that would occur from each situation is ordered from youngest to oldest. Youngest = recollapsing, critical, coastingg, accelerating = oldest.

Dark energy fills the void needed to explain why CMB says the universe is flat.

18.3 Gravitational Lensing

The object being lensed is more widely separated when the object doing the lensing is

1. **more massive**
2. **closer to the Earth**

18.4 Eras of the Universe

Era name	description	ended after	t
Planck	all 4 forces operated as one	$10^{-43}s$	
GUT	strong electroweak forces unit as GUT force	$10^{-38}s$	
Electroweak	3 forces operated: gravity, strong, electroweak	$10^{-10}s$	
Particle	Protons, neutrons both common	$10^{-3}s$	
Nucleosynthesis	fusion create helium nuclei	5 minutes	
Nuclei	H, He nuclei and electrons existed, but no neutral atoms	380,000 years	
Atoms	Neutral atoms existed, but not stars		
Galaxies	Stars and galaxies common		

The Planck era was the hottest era, the galaxy era the coolest.

18.5 Cosmic microwave background

In the era of nuclei electrons were free, and photons bounced among them. Once the age of nuclei ended the electrons were captured, and finally able to travel freely. The temperature of the universe was about 3000 K at this point and was the peak wavelength. Since then the wavelength has been decreasing linearly with the expansion of the universe.

Wavelength of CMB $\propto$ relative expansion of the universe.

The CMB has a perfect thermal radiation spectrum. Since it was originally all contained in a small area, where temperature and density could equalize.

Current temperature of the CMB is approximately 2.73 K.

19 Definitions

19.1 Basic Astronomical Objects

star is a large, glowing ball of gas that generates heat and light through nuclear fusion in its core. Our Sun is a star.

planet is a moderately large object that orbits a star and shines primarily by reflecting light from its star. According to a definition approved in 2006, an object can be considered a planet only if it (1) orbits a star; (2) is large enough for its own gravity to make it round; and (3) has cleared most other objects from its orbital path. An object that meets the first two criteria but has not cleared its orbital path, like Pluto, is designated a dwarf planet.

moon (or satellite) is an object that orbits a planet. The term satellite can refer to any object orbiting another object. asteroid A relatively small and rocky object that orbits a star.

comet is a relatively small and ice-rich object that orbits a star.

extrasolar planet is a planet that orbits a star that is not our Sun.

19.2 Collections of Astronomical Objects

solar system is the Sun and all the material that orbits it, including the planets, dwarf planets, and small solar system bodies. Although the term solar system technically refers only to our own star system (solar means of the Sun), it is often applied to other star systems as well.

star system is a star (sometimes more than one star) and any planets and other materials that orbit it.

galaxy is a great island of stars in space, containing from a few hundred million to a trillion or more stars, all held together by gravity and orbiting a common center.

cluster (or group) of galaxies is a collection of galaxies bound together by gravity. Small collections (up to a few dozen galaxies) are generally called groups, while larger collections are called clusters.

supercluster is a gigantic region of space where many individual galaxies and many groups and clusters of galaxies are packed more closely together than elsewhere in the universe.

universe (or cosmos) are the sum total of all matter and energy – that is, all galaxies and everything between them. observable universe The portion of the entire universe that can be seen from Earth, at least in principle. The observable universe is probably only a tiny portion of the entire universe.

19.3 Astronomical Distance Units

astronomical unit (AU) is the average distance between Earth and the Sun, which is about 150 million kilometers. More technically, 1 AU is the length of the semimajor axis of Earths orbit.

light-year is the distance that light can travel in 1 year, which is about 9.46 trillion kilometers.

19.4 Terms Relating to Motion

rotation is the spinning of an object around its axis. For example, Earth rotates once each day around its axis, which is an imaginary line connecting the North Pole to the South Pole.

orbit (revolution) is the orbital motion of one object around another. For example, Earth orbits around the Sun once each year.

expansion (of the universe) is the increase in the average distance between galaxies as time progresses. Note that while the universe as a whole is expanding, individual galaxies and galaxy clusters do not expand.

Doppler shift light is bluer if the object is moving towards the Earth, it is redder if the object is moving away from the Earth. The intensity of the light is related to the speed at which the object is moving toward / away from the Earth.

19.5 Telescopes

Diffraction limit The angular resolution before interference of light itself causes problems

20 Formulae and Values

Our solar system was formed 4.5 billion years ago, when about 2% of the galaxy's original Hydrogen and Helium had been converted to heavier elements. Thus the cloud which formed our galaxy was roughly 98% Hydrogen and Helium. The 2% of other materials form the core of the rocky planets in our systems, ie. the Earth.

The Andromeda galaxy is roughly 2.5 million light-years away and about 100,000 light-years in diameter. Sirius, the brightest star visible in the night sky, is 8 light-years away. Alpha Centauri, the closest star system to our own (a three star system), is 4.4 light-years away.

- $E_k = \frac{1}{2}mv^2$
- $v = \lambda f$
- Energy $= hf = \frac{hc}{\lambda}$
- $v_{\text{radial}} = \frac{\Delta\lambda}{\lambda}\ c$
- $F = G\frac{m_1 m_2}{r^2}$
- $p^2 = \frac{4\pi^2}{(M_1+M_2)*G}\ a^3$ (in our solar system years^2 = A.U.^{3})
- $L = 4\pi^2 R^2 \sigma_{SB} T^4$
- Angular separation (rad) $= \frac{\text{semi-major axis (AU)}}{\text{distance parsecs}}$
- $r_{\text{planet}} \approx r_{\text{star}} * \sqrt{\text{fraction of light blocked}}$
- Eccentricity of an ellipse: $e = \frac{f}{a}$ where f is the distance from the center to a focus
- momentum = mass * velocity
- $\text{SA}_{\text{sphere}} = 4\pi r^2$
- $\lambda_{\text{peak}} T = 2.898 * 10^{-3} m \cdot K$

- **Time dilation:** $t' = t * \sqrt{1 - \left(\frac{v}{c}\right)^2}$
- **Length contraction:** $l' = l * \sqrt{1 - \left(\frac{v}{c}\right)^2}$
- **Mass increase:** $m' = \dfrac{m}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$
- **Angular size, physical size, and distance are related as** $\frac{l_{angular}}{360} = \frac{l_{physical}}{2\pi d}$
- $v = \sqrt{\frac{M_r * G}{r}}$
  - M_r **= encircled mass**
  - r **= radius of sphere containing the mass**

21 Data

Speed of light $2.998 * 10^8 m/s$

Light year $9.461 * 10^{15}$ **m = 63 241 AU**

Observable Universe Boundary $14 * 10^9$ **ly**

Average Earth-Moon distance 385 000 km

Average Earth-Sun distance (1 AU) $1.4959 * 10^{11}$ **m**

Diameter of the Sun $1.391 * 10^6$ **km**

Planck's constant (h) $6.626 * 10^{-34} J \cdot s = 4.136 * 10^{-15} eV \cdot s$

StefanBoltzmann constant $5.67 * 10^{-8} \frac{W}{m^2 K^4}$

Gravitational constant $6.673 * 10^{-11} N \cdot (m/kg)^2$

	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Mass (10^{24} kg)	**0.330**	**4.87**	**5.97**	**0.073**	**0.642**	**1898**	**568**	**86.8**	**102**	**0.0131**
Diameter (km)	**4879**	**12,104**	**12,756**	**3475**	**6792**	**142,984**	**120,536**	**51,118**	**49,528**	**2390**
Density (kg/m^3)	**5427**	**5243**	**5514**	**3340**	**3933**	**1326**	**687**	**1271**	**1638**	**1830**
Gravity (m/s^2)	**3.7**	**8.9**	**9.8**	**1.6**	**3.7**	**23.1**	**9.0**	**8.7**	**11.0**	**0.6**
Escape Velocity (km/s)	**4.3**	**10.4**	**11.2**	**2.4**	**5.0**	**59.5**	**35.5**	**21.3**	**23.5**	**1.1**
Rotation Period (hours)	**1407.6**	**-5832.5**	**23.9**	**655.7**	**24.6**	**9.9**	**10.7**	**-17.2**	**16.1**	**-153.3**
Length of Day (hours)	**4222.6**	**2802.0**	**24.0**	**708.7**	**24.7**	**9.9**	**10.7**	**17.2**	**16.1**	**153.3**
Distance from Sun (10^6 km)	**57.9**	**108.2**	**149.6**	**0.384***	**227.9**	**778.6**	**1433.5**	**2872.5**	**4495.1**	**5870.0**
Perihelion (10^6 km)	**46.0**	**107.5**	**147.1**	**0.363***	**206.6**	**740.5**	**1352.6**	**2741.3**	**4444.5**	**4435.0**
Aphelion (10^6 km)	**69.8**	**108.9**	**152.1**	**0.406***	**249.2**	**816.6**	**1514.5**	**3003.6**	**4545.7**	**7304.3**
Orbital Period (days)	**88.0**	**224.7**	**365.2**	**27.3**	**687.0**	**4331**	**10,747**	**30,589**	**59,800**	**90,588**
Orbital Velocity (km/s)	**47.4**	**35.0**	**29.8**	**1.0**	**24.1**	**13.1**	**9.7**	**6.8**	**5.4**	**4.7**
Orbital Inclination (degrees)	**7.0**	**3.4**	**0.0**	**5.1**	**1.9**	**1.3**	**2.5**	**0.8**	**1.8**	**17.2**
Orbital Eccentricity	**0.205**	**0.007**	**0.017**	**0.055**	**0.094**	**0.049**	**0.057**	**0.046**	**0.011**	**0.244**
Axial Tilt (degrees)	**0.01**	**177.4**	**23.4**	**6.7**	**25.2**	**3.1**	**26.7**	**97.8**	**28.3**	**122.5**
Mean Temperature (C)	**167**	**464****	**15**	**-20**	**-65**	**-110**	**-140**	**-195**	**-200**	**-225**
Surface Pressure (bars)	**0**	**92**	**1**	**0**	**0.01**	**Unknown**	**Unknown**	**Unknown**	**Unknown**	**0**
Number of Moons	**0**	**0**	**1**	**0**	**2**	**67**	**62**	**27**	**14**	**5**
Ring System?	**No**	**No**	**No**	**No**	**No**	**Yes**	**Yes**	**Yes**	**Yes**	**No**
Global Magnetic Field?	**Yes**	**No**	**Yes**	**No**	**No**	**Yes**	**Yes**	**Yes**	**Yes**	**Unknown**

*** From the Earth**

**** Due to intense greenhouse effect of thick atmosphere**

Astronomical Distances

1 AU $\approx 1.496 \times 10^8$ km $= 1.496 \times 10^{11}$ m

1 light-year $\approx 9.46 \times 10^{12}$ km $= 9.46 \times 10^{15}$ m

1 parsec (pc) $\approx 3.09 \times 10^{13}$ km ≈ 3.26 light-years

1 kiloparsec (kpc) $= 1000$ pc $\approx 3.26 \times 10^3$ light-years

1 megaparsec (Mpc) $= 10^6$ pc $\approx 3.26 \times 10^6$ light-years

Universal Constants

Speed of light:	$c = 3.00 \times 10^5 \text{ km/s} = 3 \times 10^8 \text{ m/s}$
Gravitational constant:	$G = 6.67 \times 10^{-11} \dfrac{\text{m}^3}{\text{kg} \times \text{s}^2}$
Planck's constant:	$h = 6.63 \times 10^{-34} \text{ joule} \times \text{s}$
Stefan-Boltzmann constant:	$\sigma = 5.67 \times 10^{-8} \dfrac{\text{watt}}{\text{m}^2 \times \text{K}^4}$
Mass of a proton:	$m_p = 1.67 \times 10^{-27}$ kg
Mass of an electron:	$m_e = 9.11 \times 10^{-31}$ kg

Useful Sun and Earth Reference Values

Mass of the Sun: $1M_{\text{Sun}} \approx 2 \times 10^{30}$ kg

Radius of the Sun: $1R_{\text{Sun}} \approx 696{,}000$ km

Luminosity of the Sun: $1L_{\text{Sun}} \approx 3.8 \times 10^{26}$ watts

Mass of Earth: $1M_{\text{Earth}} \approx 5.97 \times 10^{24}$ kg

Radius (equatorial) of Earth: $1R_{\text{Earth}} \approx 6378$ km

Acceleration of gravity on Earth: $g = 9.8 \text{ m/s}^2$

Escape velocity from surface of Earth: $v_{\text{escape}} = 11.2 \text{ km/s} = 11{,}200 \text{ m/s}$

Astronomical Times

1 solar day (average) $= 24^h$

1 sidereal day $\approx 23^h56^m4.09^s$

1 synodic month (average) ≈ 29.53 solar days

1 sidereal month (average) ≈ 27.32 solar days

1 tropical year ≈ 365.242 solar days

1 sidereal year ≈ 365.256 solar days

Energy and Power Units

Basic unit of energy: 1 joule $= 1 \dfrac{\text{kg} \times \text{m}^2}{\text{s}^2}$

Basic unit of power: 1 watt $= 1$ joule/s

Electron-volt: 1 eV $= 1.60 \times 10^{-19}$ joule

22 Lecture Slides

22.1 Scale of the Universe

22.1.1 Objects in the Universe

- Star: A large, glowing ball of gas that generates heat and light through nuclear fusion
- Planet: A moderately large object that orbits a star; it shines by reflected light. Planets may be rocky, icy, or gaseous in composition.
- Moon: An object that orbits a planet
- Asteroid: A relatively small and rocky object that orbits a star
- Comet: A relatively small and icy object that orbits a star
- Solar System: A star and all the material that orbits it, including its planets and moons
- Nebular: An interstellar cloud of gas and/or dust
- Galaxy: A great island of stars in space, all held together by gravity and orbiting a common center
- Universe: The sum total of all matter and energy; that is, everything within and between all galaxies

22.1.2 Light Travels

Light travels at a finite speed (3000,000 km/s) so the farther away we look the farther back in time we look. Light years are distance light travels in a year (9,460,000,000,000 km).

Destination	Light travel time
Moon	1s
Sun	8s
Sirius	8 years
Andromeda	2.5 million light years

22.1.3 The Universe is Big

We can't see a galaxy 15 billion light years away (universe is 14 billion years old) because looking 15 billion light-years away means looking to a time before the universe existed.

If we reduce the size of the solar system by a factor of 10 billion the sun is the size of a grapefruit and earth is the size of a ball point (15m from the sun)and alpha centauri is 2500 miles away

The milky way galaxy has about 100 billion stars. There are around 100 billion galaxies in universe. There are more stars in the universe than grains of sand on earth. It would take more than 3000 years to count the stars in the Milky Way Galaxy at a rate of one per second, and they are spread across 100,000 light-years.

The matter in our bodies came from the Big Bang, which produced hydrogen and helium. All other elements were constructed from H and He in stars and then recycled into new star systems, including our solar system. On a cosmic calendar that compresses the history of the universe into 1 year, human civilization is just a few seconds old, and a human lifetime is a fraction of a second.

22.1.4 Earth Moves Through Space

Earth orbits the sun at an average distance of 1AU = 150 million kilometers (at 107,000 km/h) and tilted by 23.5° rotating clockwise.

The sun moves 70,000 km/h and orbits the galaxy every 230 million years.

Galaxies in our Local Group are moving away from us and the farther a galaxy is the faster it is moving, which implies that we live in an expanding universe.

22.2 Discovering the Universe for Yourself

22.2.1 View from Earth

With the naked eye we can see > 2000 stars as well as the milky way. Some of these stars are sorted into 88 constellations. These lie on the celestial sphere (all stars lie on celestial sphere).

- the ecliptic is the sun's apparent path through celestial sphere
- north celestial pole is directly above earth's north pole
- celestial equator is projection of earth's equator on celestial sphere

The milky way is a band of light making a circle around the celestial sphere (just our view into the plane of our galaxy).

22.2.2 Local Sky

An object's altitude (above horizon) and direction (along horizon) specify its location in your local sky.

- meridian: line throuh zenith and connecting N and S points on horizon

- zenith: point directly overhead
- horizon: all points 90 degress from zenith

22.2.3 Measurements

Angular size of sun	0.5 degrees
Angular size of moon	0.5 degrees
Width of finger	1 degree
Width of hand	20 degrees
Width of fist	10 degrees

Arcminutes (denoted ') are 1/60 of a degree and arcseconds are 1/60 of arcminutes (denoted ").

$$\text{angular size} = \text{physical size } \times \frac{360^\circ}{2\pi \times \text{distance}}$$

22.2.4 Star Rise

Earth rotates west to east so starts appear to move east to west. Stars near the north pole are circumpolar and never set. Starts near south pole are not seen. What constellations we see depends on latitude (but not longitude) because position on Earth determines which constellations remain below the horizon, and time of year because Earth's orbit changes the apparent location of the Sun among the stars.

The altitude of the celestial pole equals your latitude (ex if Polaris is 50° above the horizon due north you are at latitude 50°N). All constellations move counter clockwise around Polaris.

22.2.5 Seasons

Direct sunlight heats more so in the summer we are angled toward the sun so we get more direct sunlight. Sun's position varies by season (summer has is higher). Earth's distance from Sun varies by at most 3% so it cannot effect the temperature as much as the axis tilt can.

- Summer solstice: highest path (rise and set at most extreme north)
- Winter solstice: lowest path (rise and set at most extreme south) for this half of the year the sun's angle at north pole is less than 0
- Spring/Fall equinox: middle path (rise and set at exactly east and west) here the angle of sun at noon on north pole is earth's axis tilt.

Earth's axis rotates once every 26,000 years

22.2.6 The Moon

Moon's phases:

- new (6am to 6pm)
- waxing crescent (glowey bit on the right) (9am to 9pm)
- first quarter (noon to midnight)
- waxing gibbous (3pm to 3am)
- full (6pm to 6am)
- waning gibbous (9pm to 9am)
- last quarter (midnight to noon)
- waning crescent (glowey bit on the left) (3am to 3pm)

A lunar eclipse occurs when earth casts a shadown across the moon. Penumbra is a glowing ring around (due to light refraction) umbra which is strict shadow.

- full lunar eclipse - moon passes through umbra
- partial lunar eclipse - moon partially passes through umbra
- penumbral lunar eclipse - moon passes through penumbra

Eclipses only occur wiht a full moon at night.

A solar eclipse only occurs at new moon during the day.

The Moon's orbit is tilted 5 to ecliptic plane. So we have about two eclipse seasons each year, with a lunar eclipse at new moon and solar eclipse at full moon.Eclipses recur with the 18-year, 11 1/3-day saros cycle, but type (e.g., partial, total) and location may vary.

22.2.7 Ancient Planets

- Mercury
  - difficult to see; always close to Sun in sky
- Venus
  - very bright when visible, morning or evening "star"
- Mars
  - noticeably red
- Jupiter
  - very bright
- Saturn

- moderately bright

Ancients saw planets that moved eastward relative to the starts but occasionally went backwards (called retrograde). Impossible to explain with geocentric universe. The greeks rejected the heliocentric universe because they couldn't observe the stellar paralax (difference in position of a star as seen from earth) because the change in distance was too small to be measured.

22.3 Science of Astronomy

The seven days of the week were named after the sun, moon, and five visible planets (tues-mars, wed-mercury, thurs-jupiter, fri-venus, sat-saturn).

Some ancient time peices:

- Stonehenge
- Templo Mayor (mexico)
- Sun dagger marks solstice(US)
- Macchu Picu
- Polynesia were good celestial navigators
- China first to record supernovas

22.3.1 Ancient Greeks

Greeks were the first people known to make models of nature. They tried to explain patterns in nature without resorting to myth or the supernatural.

Eratosthenes measured the size of earth in 240BC: Distance between two cities (Syene and Alexandria) was 5000 stadia, using a stick in a hole he could see that when the sun was directly overhead of alexandria it was off by 7 degrees in Syene. 7/360 * (circumference of earth) = 5000 stadia. Was only off by 2000km.

Greeks used geocentric model(heaves must be perfect with everything being perfect spheres and circles). This couldnt explain retrograde motion. Ptolemy came up with the most sphisticated geocentric model and it was accurate enough to be in use for 1500 years. He explained retrograde motion by having planets make little circles occasionally in their larger orbit of earth.

Which of the following is NOT a fundamental difference between the geocentric and Sun-centered models of the solar system?

1. Earth is stationary in the geocentric model but moves around Sun in Sun-centered model.
2. Retrograde motion is real (planets really go backward) in geocentric model but only apparent (planets don't really turn around) in Sun-centered model.

3. Stellar parallax is expected in the Sun-centered model but not in the Earth-centered model.
4. F The geocentric model is useless for predicting planetary positions in the sky, while even the earliest Sun-centered models worked almost perfectly.

Greek knowledge was preserved through:

- The Muslim world preserved and enhanced the knowledge they received from the Greeks.
- Al-Mamun's House of Wisdom in Baghdad was a great center of learning around A.D. 800.
- With the fall of Constantinople (Istanbul) in 1453, Eastern scholars headed west to Europe, carrying knowledge that helped ignite the European Renaissance.

22.3.2 Copernican Revolution

Copernicus:

- Proposed a Sun-centered model (published 1543)
- Used model to determine layout of solar system (planetary distances in AU) But . . .
- The model was no more accurate than the Ptolemaic model in predicting planetary positions, because it still used perfect circles.

Tycho Brahe:

- Compiled the most accurate (one arcminute) naked eye measurements ever made of planetary positions.
- Still could not detect stellar parallax, and thus still thought Earth must be at center of solar system (but recognized that other planets go around Sun).
- Hired Kepler, who used Tycho's observations to discover the truth about planetary motion.

Johannes Kepler:

- Kepler first tried to match Tycho's observations with circular orbits
- But an 8-arcminute discrepancy led him eventually to ellipses.

Kepler's laws:

1. The orbit of each planet around the Sun is an ellipse with the Sun at one focus
2. As a planet moves around its orbit, it sweeps out equal areas in equal times (means that a planet travels faster when it is nearer to the sun)

3. More distant planets orbit the Sun at slower average speeds, obeying the relationship: $p^2 = a^3$ where p = orbital period in years and a = avg. distance from Sun in AU

Gelileo fixed some flaws in Compernican revolution:

- **Earth could not be moving because objects in air would be left behind.**
  - **Galileo's experiments showed that objects in air would stay with Earth as it moves, showed that objects will stay in motion unless a force acts to slow them down**
- **Non-circular orbits are not "perfect" as heavens should be.**
  - **Tycho's observations of comet and supernova already challenged this idea.**
  - **Galileo used telescope to spot imperfections (sunspots, and craters on the moon)**
- **If Earth were really orbiting Sun, we'd detect stellar parallax.**
  - **Galileo showed stars must be much farther than Tycho thought in part by using his telescope to see the Milky Way is countless individual stars. If stars were much farther away, then lack of detectable parallax was no longer so troubling.**

He also saw Jupiter's moons so not everything was orbiting earth. Proved Venus' orbit of the sun and used it to explain retrograde motion.

22.3.3 Scientific Theory

Science Hallarks:

- **Modern science seeks explanations for observed phenomena that rely solely on natural causes.(A scientific model cannot include divine intervention)**
- **Science progresses through the creation and testing of models of nature that explain the observations as simply as possible. (Simplicity = "Occam's razor")**
- **A scientific model must make testable predictions about natural phenomena that would force us to revise or abandon the model if the predictions do not agree with observations**

A scientific theory must:

- **Explain a wide variety of observations with a few simple principles**
- **Must be supported by a large, compelling body of evidence**
- **Must NOT have failed any crucial test of its validity**

22.3.4 Astrology

Astronomy is a science focused on learning about how stars, planets, and other celestial objects work. Astrology is a search for hidden influences on human lives based on the positions of planets and stars in the sky.

22.4 Making Sense of the Universe: Understanding Motion, Energy, and Gravity

Momentum = mass X velocity.

Angular momentum = mass x velocity x radius

Remember that force is based on acceleration not speed.

Remember that weight force and mass is matter

Newtons Laws:

- An object moves at constant velocity unless a net force acts to change its speed or direction.
- Force = mass x acceleration
- For every force, there is always an equal andopposite reaction force

Conservation Laws:

- conservation if momentum
  - The total momentum of interacting objects cannot change unless an external force is acting on them.
  - Interacting objects exchange momentum through equal and opposite forces.
- conservation of angular momentum
  - The angular momentum of an object cannot change unless an external twisting force (torque) is acting on it.
  - Earth experiences no twisting force as it orbits the Sun, so its rotation and orbit will continue indefinitely.

Types of energy:

- Kinetic (motion)
- Radiative (light)
- Potential (stored)
- Thermal: The collective kinetic energy of many particles
  - Temperature is the average kinetic energy of the many particles in a substance

- Gravitational Potential
  - In space, an object or gas cloud has more gravitational energy when it is spread out than when it contracts. A contracting cloud converts gravitational potential energy to thermal energy
  - $F_g = G\frac{M_1 M_2}{d^2}$
  - items orbit around their center of mass (usually close to the big thing they are orbiting)
- Mass: $E = mc^2$
  - A small amount of mass can release a great deal of energy (for example, an H-bomb).
  - Concentrated energy can spontaneously turn into particles (for example, in particle accelerators).

We combine Newton's law of gravity and Keplers orbital law:

$$p^2 = \frac{4\pi^2}{G(M_1+M_2)}a^3$$

p = orbital period
a = average orbital distance
M = object masses

The total orbital energy is the sum of gravitational and kinetic and remains the same (which is why we go faster closer). This means its very hard to change an orbit.

Earth's escape velocity is 11km/s (40000km/h)

Tides:

- caused by moon being closer to one side
- depends on phase because of sun's position
- tidal friction slows earths rotation, making moon get farther from Earth

22.5 Light and Matter: Reading Messages from the Cosmos

How do light and matter interact?

- emission/absorption (determines brightness)
- transmission
- reflection (determines color)

22.5.1 Waves

Speed of light = wavelength x frequency
Photon energy = (6.626*10$10^-34$) plancks constant * frequency

Polarization is the direction a light wave is vibrating

22.5.2 Matter

Vocabulary:

- **Atomic number = # of protons in nucleus**
- **Atomic mass number = # of protons + neutrons**
- **Isotope: same # of protons but different # of neutrons**
- **Ionization: stripping of electrons, changing atoms into plasma**
- **Dissociation: breaking of molecules into atoms**
- **Evaporation: breaking of flexible chemical bonds, changing liquid into solid**
- **Melting: breaking of rigid chemical bonds, changing solid into liquid**

22.5.3 Light

Three types of spectra: emission line (specific elements emit light at certain wavelengths due to electrons jumping), continuous, absorption line (a cloud in between absorbes some light).

22.5.4 Thermal Radiation

Hotter objects emit more light at all frequencies per unit area. Hotter objects emit photons with a higher average energy.

Wein's law approximates starts to blackbody radiators (absorbs all kinds of radiation and emits energy regardless). Peak wavelength times the temperature is a constant (Plank radiation constant): $\lambda_{peak}T = 2.898 \times 10^3$. This also means that stars of shorter wavelength (blue) are hotter.

Interpretting Spectrum:

- **look for parts of the visible spectrum that have lower intensity (low intensity blue light means it looks red and vice versa)**
- **look for a spike in the infrared to indicate tempurature**
- **look for absorbtion lines for the content of the atmosphere**
- **look for emission lines to describe the upper atmosphere**

22.5.5 Doppler effect

As something moves towards us its spectrum gets shifted

1. measure spectrum of stars composition in lab (heat gases)
2. measure spectrum of star
3. compare placement of lines
4. if wavelength of star is longer than lab (it shifted right/red) its moving away
5. $f_{star} = \sqrt{\frac{c-v}{c+v}} \times f_{lab}$

When an object is rotating the width of its spectral lines can tell us how fast its spinning.

22.6 Telescopes: Portals of Discovery

Two most important properties of telescopes:

- Light-collecting area: Telescopes with a larger collecting area can gather a greater amount of light in a shorter time.
  - $A = \pi r^2$
- Angular resolution: Telescopes that are larger are capable of taking images with greater detail.
  - minimum angular separation the telescope can distinguish, diffraction limit is caused by interference of light waves in telescope (larger = less interference)

Two basic designs:

- refracting: focus light with lenses
  - need to be long and large with heavy lenses
- reflecting: focus light with mirrors
  - larger diameters
  - most common

Uses of telescopes:

- imaging: pictures
  - record only one color at a time
  - use color to represent invisible light
- spectroscopy: breaking up light spectra
- time monitoring: watching how light output of object varies with time

Problems:

- twinkling: turbulence in earths atmosphere distorts veiw and causes stars to twinkle (can be fixed by rapidly changing the shape of the mirror)
- light pollution
- certain wavelengths cannot pierce atmosphere
  - gamma rays - 10km, balloons
  - x rays - 100km, rockets
  - ultraviolet - some reach earth but some require rockets
  - visible - reaches ground
  - infrared - 5km, some mountains, planes
  - radio - reaches ground

Telescopes:

- radio: giant mirror that reflects radio waves to focus point
- infrared and ultraviolet: like visible telescopes but need to be above the atmosphere
- x-ray: also need to be above atmosphere, mirrors arranged to focus x-ray photons through grazing bounces off of mirrors
- gamma-ray: also need to be above atmosphere, fucking hard to focus gamma rays

Multiple telescopes (Inferometry) increase the angular resolution of a single large image.

22.7 Our Planetary System

What does the solar system look like?

- There are eight major planets with nearly circular orbits.
- Dwarf planets are smaller than the major planets and some have quite elliptical orbits.
- Planets all orbit in same direction and nearly in same plane.

Comparative Planetology (find patterns among planets)

- Planets are very tiny compared to distances between them.
- All large bodies in the solar system orbit in the same direction and in nearly the same plane and most rotate in the same direction
- two planet types

  - terrestrial
  - jovian
- Many rocky asteroids and icy comets populate the solar system.

Exceptions:

- Uranus spins sideways
- earth has a large moon
- venus rotates backwards

Objects:

- sun
  - Over 99.9% of solar system's mass
  - Made mostly of H/He gas (plasma)
  - Converts 4 million tons of mass into energy each second
- mercury
  - Made of metal and rock; large iron core
  - Desolate, cratered; long, tall, steep cliffs
  - Very hot, very cold: 425C (day), 170C (night)
- venus
  - Nearly identical in size to Earth; surface hidden by clouds
  - Hellish conditions due to an extreme greenhouse effect
  - Even hotter than Mercury: 470C, day and night
- earth
  - An oasis of life
  - The only surface liquid water in the solar system
  - A surprisingly large moon
- mars
  - Looks almost Earth-like, but don't go without a spacesuit!
  - Giant volcanoes, a huge canyon, polar caps, more
  - Water flowed in distant past; could there have been life?
- jupiter
  - Much farther from Sun than inner planets
  - Mostly H/He; no solid surface

- 300 times more massive than Earth
- Many moons, rings
  - Io (shown here): active volcanoes all over
  - Europa: possible subsurface ocean
  - Ganymede: largest moon in solar system
  - Callisto: a large, cratered "ice ball
- saturn
  - Giant and gaseous like Jupiter
  - Spectacular rings:Rings are NOT solid; they are made of countless small chunks of ice and rock, each orbiting like a tiny moon.
  - Many moons, including cloudy Titan
- uranus
  - Smaller than Jupiter/Saturn; much larger than Earth
  - Made of H/He gas and hydrogen compounds(H2O, NH3, CH4)
  - Extreme axis tilt
  - Moons and rings
- neptune
  - Similar to Uranus (except for axis tilt)
  - Many moons (including Triton)
- dwarf planets
  - Much smaller than major planets
  - Icy, comet-like composition
  - Pluto's main moon (Charon) is of similar size

Planet	Relative Size	Average Distance from Sun (AU)	Average Equatorial Radius (km)	Mass (Earth = 1)	Average Density (g/cm^3)	Orbital Period	Rotation Period	Axis Tilt	Average Surface (or Cloud-Top) Temperature[b]	Composition	Known Moons (2012)	Rings?
Mercury		0.387	2440	0.055	5.43	87.9 days	58.6 days	0.0°	700 K (day) 100 K (night)	Rocks, metals	0	No
Venus		0.723	6051	0.82	5.24	225 days	243 days	177.3°	740 K	Rocks, metals	0	No
Earth		1.00	6378	1.00	5.52	1.00 year	23.93 hours	23.5°	290 K	Rocks, metals	1	No
Mars		1.52	3397	0.11	3.93	1.88 years	24.6 hours	25.2°	220 K	Rocks, metals	2	No
Jupiter		5.20	71,492	318	1.33	11.9 years	9.93 hours	3.1°	125 K	H, He, hydrogen compounds[c]	67	Yes
Saturn		9.54	60,268	95.2	0.70	29.5 years	10.6 hours	26.7°	95 K	H, He, hydrogen compounds[c]	62	Yes
Uranus		19.2	25,559	14.5	1.32	83.8 years	17.2 hours	97.9°	60 K	H, He, hydrogen compounds[c]	27	Yes
Neptune		30.1	24,764	17.1	1.64	165 years	16.1 hours	29.6°	60 K	H, He, hydrogen compounds[c]	13	Yes
Pluto		39.5	1160	0.0022	2.0	248 years	6.39 days	112.5°	44 K	Ices, rock	5	No
Eris		67.7	1200	0.0028	2.3	557 years	1.08 days	78°	43 K	Ices, rock	1	No

22.7.1 Spacecraft Exploration

Flyby: flys past a planet (usually a slingshot type path), cheapest but gathers less data

Orbiters: go into orbit around object, more time to gather data

Probes and Landers: land on surface, most expensive

Combination: an orbiter drops a lander and continues its orbit

22.8 Other Planetary Systems: The New Science of Distant Worlds

Its hard to learn about extrasolar planets because planets are too close to their star and too dark to easily see.

Planet Detection:

- **Direct: pictures or spectra of the planets themselves**
- **Indirect: measurements of stellar properties revealing the effects of orbiting planets**

Stars wobble back and forth a bit because they are also pulled by their planets' gravity which we can use to reveal the mass (this is a lower limit since we would need to know its tilt to be accurate) and orbit of planets. These changes are very hard to see and we need to use doppler technique to measure them (accurate to 1m/s of movement).

The first extrasolar planet was discovered around 51 Pegasi when a 4 day orbital cycle was found. This means that the planet is very close to the star (it also has a mass similar to jupiter)

If you see a star with a wobble of greater than 1 year it has a planet closer than 1AU.

We can also watch for changes in brightness when a planet passes infront of the star called a transit. We use this to tell the planet's radius. The Kepler mission was launched to look for these tiny changes in brightness.

We can also use gravitational lensing to see how a planet's mass bends the light of a star and dust disks to see gaps in disks of dust and gas around stars where planets are.

We can also monitor the change in spectrum during a planet's transit across its star to know about its atmosphere composition. Similarly we can measure the surface tempertaure of the planet by seeing how the temperature of the star changes as the planet passes it.

Most detected planets have orbits smaller than Jupiter's but this is because planets at a farther distance are harder to detect. Some extrasolar planets have more eliptical orbits and tend to have greater mass than Jupiter (this is also because smaller mass planets are harder to detect).

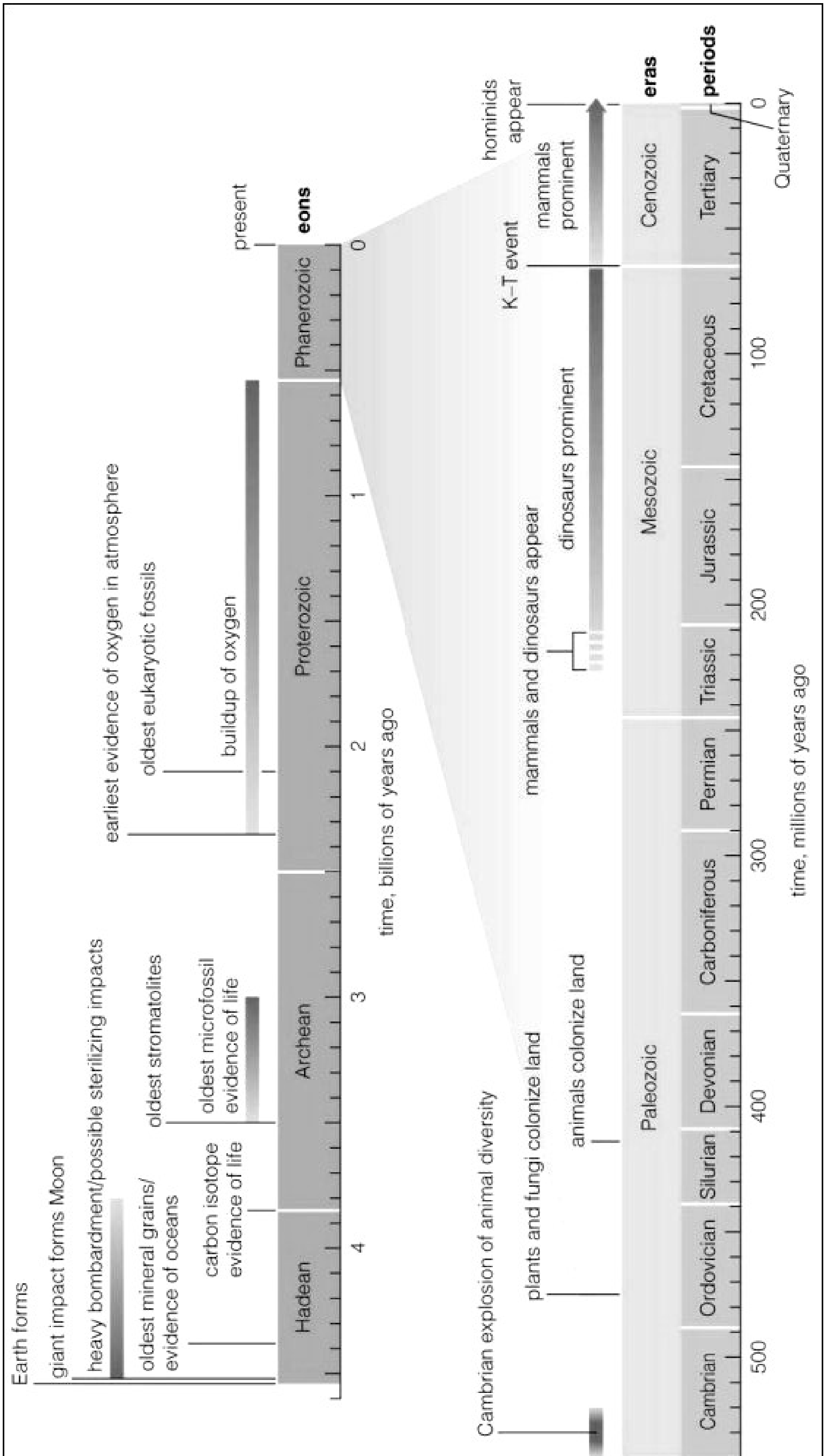
Extrasolar planet suprprises:

- **highly elliptical orbits**
- **huge diversity of size and density**
- **massive planets very close to their start (hot Jupiters)**
  - **Nebular theory predicts that massive planets cannot form inside of frost line ($<<$ 5AU)**
  - **may be explained by planetary migration or gravitational encounters**
    - **planetary migration: young planets spin very quickly and can form disks which can tug the planet's orbit inward**
    - **gravitational encounters: two massive planets getting two close to each other can result in one getting ejected into a highly elliptical orbit, multiple ones can cause a inward migration, this is due to one planet transfering energy and angular momentum to the other**

The above weirdness caused a re-evaluation of Nebular Theory.

22.9 Life in the Universe

Life on earth started 3.85 billion years ago shortly after a heavy bombardment as fossils and carbon dating imply. Fossiles tend to be found in sedimentary rock.



Earth forms
giant impact forms Moon
heavy bombardment/possible sterilizing impacts
oldest mineral grains/ evidence of oceans
carbon isotope evidence of life
oldest stromatolites
oldest microfossil evidence of life
earliest evidence of oxygen in atmosphere
oldest eukaryotic fossils
buildup of oxygen
present
eons
Hadean
Archean
Proterozoic
Phanerozoic
4
3
2
1
0
time, billions of years ago
Cambrian explosion of animal diversity
plants and fungi colonize land
animals colonize land
mammals and dinosaurs appear
dinosaurs prominent
K–T event
mammals prominent
hominids appear
eras
Paleozoic
Mesozoic
Cenozoic
periods
Cambrian
Ordovician
Silurian
Devonian
Carboniferous
Permian
Triassic
Jurassic
Cretaceous
Tertiary
Quaternary
500
400
300
200
100
0
time, millions of years ago

We all know that life came about through evolution. Genetics builds a tree of life through relationships that implies a common ancestor for all life probably similar to bacteria found deep in the ocean near volcanic vents. We still dont know how that common ancestor came to be. The Miller-Urey experiment (among others) shows that the building blocks of life can arise spontaneously under the conditions of early earth.

Chemicals to Life:

1. Naturally forming organic molecules are building blocks of life
2. Clay minerals catalyze production of RNA and membranes that form pre-cells
3. Molecular natrual selection favors efficient self-replicating RNA molecules
4. True living cells with RNA genome give rise to RNA world
5. DNA evolves from RNA and biological evolution continues

One idea is that live could have come from another planet (Venus, Earth, and Mars exchanged tones of rock and some microbes can survive for years in space).

Brief History of life:

- 4.4 billion years - early oceans form
- 3.5 billion years - cyanobacteria start releasing oxygen
- 2.0 billion years - oxygen begins building up in atmosphere
- 540500 million years - Cambrian Explosion
- 22565 million years - dinosaurs and small mammals (dinosaurs ruled)
- Few million years - earliest hominids

Oxygen didn't always exist so readily on earth. The evolution of cyanobacteria kicked it off by releasing oxygen to the atmosphere using photosynthesis.

(Bear)Necessity of Life:

- nutrient source
- energy
- liquid water

22.9.1 Life on Other Planets

Erosion lines on mars imply that it had liquid water in its distant past, there is still subsurface ice would could result in near surface water near its volcanoes. The Curiosity rover landed on mars to investigate the habitability of the planet.

Another potential is the moon Europa which we think has a layer of liquid water or warm convecting ice. Two other Jupiter moons, Ganymede and Callisto also show evidence of subsurface oceans. Very little energy reaches these moons, but life may be possible.

The moon Titan is much too cold for liquid water (there may be some deep under the surface) but it does have lakes of liquid methane.

Encelandus has ice foundations that suggest it may have a subsurface ocean.

22.9.2 Life Outside our Solar System

Habitable Solar System:

- old enough to allow time for evolution (no high mass stars, too young, 1% of systems)
- need to have stable orbits (might rule out multistar systems, 50% of systems)
- must have habitable zone (place where planets of the right size could have liquid water), larger stars have larger zones

There are billions of stars in the milky way alone that fulfill the above constraints.

It is very hard to spot a earth like planet due to their size and distance from their star (see previous section on finding extrasolar planets for a better explanation). We launched Kepler specifically to look at 100,000 stars for habitable planets and future inferometers may be precise enough to see earth-sized planets.

We can also use spectrometry to see the composition of planets to determine if they have the elements necessary for life.

22.9.3 Earth-like Planets

Some scientists argue that the proportions of heavy elements need to be just right for the formation of habitable planets. If so, then Earth-like planets are restricted to a galactic habitable zone.

Some scientists argue that the proportions of heavy elements need to be just right for the formation of habitable planets. If so, then Earth-like planets are restricted to a galactic habitable zone.

Some scientists argue that plate tectonics and/or a large moon are necessary to keep the climate of an Earth-like planet stable enough for life.

We dont know how important the above concerns are so its very hard to make a guess as to how common earth-like planets are and how many would be habitable.

22.9.4 The Search for Extraterrestrial Intelligence

The drake equation tries to calculate how many civilization we could communicate with exist

$$N_{HP} \times f_{life} \times f_{civ} \times f_{now}$$

N_{HP} = total number of habitable planets in galaxy = probably billions
f_{life} = fraction of habitable planets with life = hard to say (near 0 or 1)
f_{civ} = fraction of life-bearing planets with civilization at some time = took 4 billion years on earth
f_{now} = fraction of civilizations around now = depends on if civilizations survive long-term

Humans are not very exceptional (not too far from a line of best fit) in our brain mass to body mass ratio.

SETI is designed to look for deliberate signals from extraterrestrial civilizations and even to send some messages of our own.

22.9.5 Interstellar Travel and Communications

Current spacecrafts travel at one ten thousandth of the speed of light which means it would take a ridiculous amount of time to get to the nearest stars. We sent a message out with Voyager in hopes of reaching one someday.

Problems with space travel:

- Far more efficient engines are needed.
- Energy requirements are enormous.
- Ordinary interstellar particles become like cosmic rays.
- Social complications of time dilation.

Fermi's paradox suggests that civilizations should be very common in our galaxy so why haven't we found any.

Explanations:

- life/civilization is much rarer than we might have guessed
- Civilizations are common, but interstellar travel is not
  - interstellar travel is more difficult than we think.
  - the desire to explore is rare.
  - civilizations destroy themselves before achieving interstellar travel.
- we just haven't met them yet

22.10 Space and Time

Einstein's Theories of Relativity:

- Special Relativity: usual ideas of space and time change as we approach the speed of light ($E = mc^2$)
  - no object can travel faster than light
  - observing a object near the speed of light:
    - time slows down
    - length contracts in direction of motion
    - mass increases
  - simultaneousness changes based on your frame of reference
- General Relativity: new views of gravity

Motion is relative. Usually how fast your percieve something is based on your velocity compared to it. The exception is light which always is seen at the same speed (called absolute relativity)

Postulates of special relativity:

- laws of nature are the same for everyone
- speed of light is the same for everyone

Time Dilation:

$$t_1 = t_0 \sqrt{1 - \left(\frac{v^2}{c^2}\right)}$$

Length Contraction:

$$l_1 = l_0 \sqrt{1 - \left(\frac{v^2}{c^2}\right)}$$

Mass Increase:

$$m_1 = \frac{m_0}{\sqrt{1 - \left(\frac{v^2}{c^2}\right)}}$$

Since no information can be transfered faster than the speed of light objects traveling near the speed of light will perceived information at different rates since the information is moving much more slowly relative to their speed.

22.10.1 Tests for Relativity

Michelson-Morley experiment found evidence for the absoluteness of the speed of light in 18887.

Time dilation occurs often to subatomic particles in accelerators.

Time dilation discovered with airplanes and very precise clocks.

$E = mc^2$ verified by measurements taken of the sun.

If the speed of light were not absolute light coming from a car moving towards you would travel at 100km/hr + c and a car moving parallel to you would be see at 100 km/hr so witnessing their collision would look very odd.

22.11 Searching the Stars

22.11.1 Brightness

The brightness of a star depends on both distance and luminosity (amount of power a star radiates in energy per second, ie. Watts). The apparent brightness is the amount of starlight that reaches Earth in energy per second per square meter.

In concentric spheres, the amount of luminsoty through each sphere is identical, ie. we can divide luminosity by area to find brightness ($b = \frac{l}{2\pi d^2}$).

The brightness at a distance three times farther, then, is, one-ninth as much.

Given the parallax angle p in arcseconds, the distance in parsecs is the inverse of p and the distance in light-years is $d = 3.26 * \frac{1}{p}$.

We define magnitude m and apparent magnitude M as and ratio in luminosity is equal to $(100^{\frac{1}{5}})^{M_1 - M_2}$ and the ratio in apparent brightness is $(100^{\frac{1}{5}})^{m_1 - m_2}$. Thus, the birghter a star is, the lower its magnitude. We can think of magnitude as a "ranking" of stars by brightness.

22.11.2 Star Spectrums

Absorption lines in a star's spectrum tell us its ionization level. These lines also correspond to a spectral type which revels its temperature (from hottest to coolest: O B A F G K M).

22.11.3 Thermal Radiation

Hotter objects emit more thermal radiation at all frequencies.

The hottests stars are approximately $50,000K$, the coolest are $3,000K$. Ours is roughly $5,800K$. Note that these are surface temperatures: our Sun's core has a temperature of roughly ten million Kelvin.

Note that the mass of these suns range from 0.08 to 100 timex the mass of our Sun.

The life expectancy of our star is 10 billion years. A star ten times more massive uses 10^4 times as much fuel, so lasts only 10 million years.

22.11.4 Binary Systems

About half of all stars are in binary systems.

22.12 Patterns Among Stars

An H-R diagram plots the luminosity and temperature of stars. Most stars fall on its main sequence.

Detailed modeling of the oldest global clusters reveal they are about 13 billion years old.

22.13 Stellar Nurseries

Stars form in dark clouds of dusty gas in interstellar space. The gas between stars is called the interstellar medium.

The molecular clouds – which contain the bulk of matter in interstellar space – have a temperature of ten to thirty Kelvin and densities of approx 300 molecules per cubic cm.

Long wavelength light such as infrared light passes through these clouds more easily than visible light; this is why we can see the center of the Milky Way only with infrared light.

Gravity can create stars only if it can overcome the force of thermal pressure within the cloud. A typical cloud must contain at least a few hundred solar masses to overcome this pressure.

Gravity within a contracting gas cloud becomes smaller as the gas becomes denser; thus it can cause the cloud to break apart into fragments which may each form a star.

As contraction packs molecules closer, it becomes difficult for infrared and radio photons to escape. Thermal energy and pressure then build up. This slows down contractions, and the center of the cloud fragment becomes a protostar.

Protostars *must* be rotating in order to form planets.

More low-mass stars tend to form than high-mass ones.