PART 1

1. Stellar Evolution

Stellar evolution describes the lifecycle of a star, from its formation to its eventual death. The process is influenced by gravity, pressure, and nuclear fusion.

Stellar Lifecycle:

Giant Gas Cloud → Protostar → T-Tauri Phase → Main Sequence → Red Giant → Fusion of heavier elements → Supernova or Planetary Nebula.

Stages in Stellar Evolution:

1. Giant Gas Cloud (Molecular Cloud)
   - A cold, dense region of gas and dust where stars are born.
2. Protostar
   - A collapsing gas cloud, still too cool for fusion, but heating up.
3. T-Tauri Phase
   - A young star that is not yet fusing hydrogen. It exhibits strong solar winds and variability in brightness.
4. Main Sequence
   - The stable phase where hydrogen is fused into helium in the core.
5. Red Giant
   - When hydrogen is depleted, the star expands, and helium begins to fuse into heavier elements.
6. Fusion of Heavier Elements
   - Stars begin to fuse heavier elements like carbon and oxygen once helium runs out.
7. Supernova / Planetary Nebula
   - High-mass stars explode as supernovae, while low-mass stars shed outer layers to form planetary nebulae, leaving behind white dwarfs.

2. Stellar Classification

Stars are classified based on their temperature, luminosity, and spectral features.

Spectral Types:

- OBAFGKM: Classification from hottest to coolest stars.
  - O: ~45,000 K (hottest)
  - M: ~2,400 K (coolest)

Luminosity Classes:

- I: Supergiants
- II: Bright giants
- III: Giants
- IV: Subgiants
- V: Main Sequence (Dwarfs)
- D: White dwarfs

Spectral Features:

- Absorption Spectrum: Dark lines in the spectrum caused by atoms absorbing specific wavelengths of light.
- Emission Spectrum: Bright lines indicating light emitted by atoms.

3. Spectroscopy and Chemical Composition

What is Spectroscopy?

- The study of light split into its component wavelengths to determine the composition, temperature, and motion of celestial objects.

Applications:

- Chemical Composition: Identifying elements based on absorption and emission lines.
- Temperature & Density: Determining the temperature and density of stars, planets, and galaxies.
- Motion: Using the Doppler effect to measure velocity (e.g., detecting exoplanets).

Spectroscopy in Astronomy

- **What is Spectroscopy?**
    - Spectroscopy breaks light into its components to analyze stars, planets, and galaxies.
    - Light from celestial bodies carries information about their composition, temperature, and more.
    - A prism or diffraction grating is used to split light into its spectrum, revealing useful data.
- **Historical Development:**
    - In the early 19th century, Fraunhofer and Kirchhoff discovered absorption lines in sunlight. These dark lines are created when certain elements absorb light at specific wavelengths.
- **Key Spectral Types:**
    - **Absorption Spectrum**: Light passes through gas, and specific wavelengths are absorbed, leaving dark lines.
    - **Emission Spectrum**: Re-emitted light from gas creates bright lines, which can identify elements.
- **Applications of Spectroscopy:**
    - Identifies chemical elements through absorption and emission lines.
    - Determines temperature, density, and other physical properties of objects.
    - Measures motion using the Doppler Effect (e.g., star/galaxy velocity, exoplanet detection).
    - Analyzes the composition of stars, galaxies, and exoplanets.
    - Helps determine distance to galaxies.

- **Spectrographs:**
  - More advanced than prisms, spectrographs spread light into a detailed spectrum.
  - Use CCD detectors for precise data recording.
  - Instruments include UVES, CRIRES, FLAMES, VIMOS, KMOS, MUSE, and SINFONI.
  - These instruments help observe specific objects or entire regions.
- **Spectroscopy's Future:**
  - Upcoming spectrographs (e.g., for the Extremely Large Telescope (ELT)) aim to analyze exoplanet atmospheres for signs of life.
  - Focus will be on detecting biosignatures in exoplanet atmospheres.
- **Notable Features of Modern Spectrographs:**
  - Operate across multiple wavelengths, from ultraviolet to infrared.
  - Spectral resolution varies; higher resolution means more detailed information.
- **Examples of Current Instruments:**
  - X-shooter: Spectrograph that covers a wide range of wavelengths from ultraviolet to infrared.

4. Luminosity and Blackbody Radiation

Luminosity:

• Definition: The total energy emitted by a star per unit time, independent of distance.

• Formula:L=4πR2σT4$L=4\pi R2\sigma T4$where LL is luminosity, RR is radius, TT is temperature, and σσ is the Stefan-Boltzmann constant.

Blackbody Radiation:

• Describes the relationship between an object's temperature and the wavelength of light it emits.

• Wien's Law: The peak wavelength of radiation shifts with temperature.

5. Color Index

• A measure of a star's color, which correlates with its temperature.

• Indicates the distribution of a star's energy across the electromagnetic spectrum.

6. Hertzsprung-Russell (H-R) Diagram

Purpose:

• Plots stars according to their luminosity and temperature to understand their evolution.

Key Features:

• X-Axis: Temperature (from hot O-type stars on the left to cool M-type stars on the right).

• Y-Axis: Luminosity (from dim white dwarfs at the bottom to bright supergiants at the top).

• Main Sequence: Stars fusing hydrogen into helium.

- Post-Main Sequence: Evolution to red giants, supergiants, or white dwarfs.

7. Star Formation and Protostars

Molecular Clouds:

- Cold, dense regions of gas and dust where stars are born.
- Example: Orion Nebula.

Protostar:

- A young star forming from a collapsing gas cloud. Fusion has not yet begun.

T-Tauri Stars:

- Young stars not yet in stable fusion. They exhibit variability and intense solar winds.

Herbig-Haro Objects:

- Glowing regions formed when jets of gas from protostars collide with surrounding gas and dust.

8. Stellar Remnants

- White Dwarfs: Dense remnants of low-mass stars.
- Neutron Stars: Extremely dense remnants of high-mass stars after supernovae.
- Black Holes: Collapse of stars with masses greater than ~25 solar masses.

9. Planet Formation and Protoplanetary Disks

Brown Dwarfs:

- Objects that are too small to initiate hydrogen fusion but too large to be considered planets.

Protoplanetary Disks:

- Rotating disks of gas and dust surrounding a young star, forming the raw material for planets.

Debris Disks:

- Disks of dust and small debris surrounding a mature star, typically after planets have formed.

10. Exoplanets

Types of Exoplanets:

- Gas Giants: Large, primarily hydrogen-helium planets (e.g., Jupiter).
- Neptunes and Ice Giants: Planets with thicker atmospheres of hydrogen, helium, and methane.
- Sub-Neptunes: Rocky planets that have lost their hydrogen-rich atmospheres.
- Super-Earths: More massive than Earth but lighter than ice giants.
- Terrestrial Planets: Rocky planets with solid surfaces (e.g., Earth, Mars).

11. Supernovae and Stellar Death

Supernova Types:

- Type I: No hydrogen present (white dwarf in a binary system).
- Type II: Result of massive star collapse, leading to neutron stars or black holes.

Impact:

- Supernovae distribute heavy elements across the galaxy.

12. Galaxies and Cosmology

Types of Galaxies:

- Spiral: E.g., Milky Way.
- Elliptical: Older, less active galaxies.
- Irregular: No defined shape.

Hubble's Tuning Fork Diagram:

- Classifies galaxies based on shape and structure.

Cosmic Microwave Background (CMB):

- Evidence of the Big Bang, showing the earliest light from the universe.

Dark Matter:

- Inferred from the way galaxies rotate and the effect of gravity on galaxy clusters.

13. Exoplanet Detection Methods

Transit Method:

- Detects a dip in light when a planet crosses in front of its host star.

Radial Velocity:

- Measures the wobble of a star caused by the gravitational pull of an orbiting planet.

Habitable Zones:

- The region around a star where liquid water could exist on a planet's surface.

14. Telescopes and Observation Techniques

Types of Telescopes:

- Optical Telescopes: Reflecting and refracting.
- Radio Telescopes: Detect radio waves from space.
- Space-based Telescopes: E.g., Hubble, James Webb Space Telescope (JWST).

Techniques:

- Spectroscopy: Used for analyzing chemical composition, temperature, and motion.
- Adaptive Optics: Corrects atmospheric distortion for clearer images.

15. Key Astronomical Objects and Missions

Notable Objects:

- Betelgeuse: A red supergiant nearing supernova.
- Andromeda Galaxy: On a collision course with the Milky Way.

Missions:

• Voyager: Exploring the outer solar system.
• JWST: Studying distant exoplanets and galaxies.
• Kepler/TESS: Missions focused on discovering exoplanets.

PART 2

Orbital Motions of Planetary Systems

Orbital Mechanics

- **Definition**: The study of the motions of celestial bodies under the influence of gravity.
- Key Forces:
  - **Gravitational Force**: Affects the motion of planets, moons, and satellites.
  - **Centripetal Force**: Keeps objects in circular or elliptical orbits.
- **Newton's Law of Gravitation**:
  F=Gm1m2/r2, where:
  - G: Gravitational constant.
  - m1,m2: Masses of two objects.
  - r: Distance between their centers.

Kepler's Laws of Planetary Motion

1. **First Law (Law of Ellipses)**:
   Planets move in elliptical orbits with the Sun at one focus.
2. **Second Law (Law of Equal Areas)**:
   A line joining a planet and the Sun sweeps out equal areas in equal time intervals.
   - Implies planets move faster when closer to the Sun (perihelion) and slower when farther (aphelion).
3. **Third Law (Harmonic Law)**:
   The square of the orbital period (T) of a planet is proportional to the cube of its semi-major axis (a):
   T^2∝a^3 or T^2/a^3 = constant.

Rotation and Circular Motion

- **Angular Velocity (ω)**: Rate of rotation, ω=Δθ/Δt .
- **Centripetal Acceleration**:
  ac=v^2/r or ac=rω^2, where:
  - v: Tangential velocity.
  - r: Radius of circular motion.
- **Orbital Velocity**:
  v=square root GM/r, where:

- M: Mass of the central body (e.g., the Sun).
- **Escape Velocity**:
  Vescape=square root 2GM/r.

Calculating Distances to Stars and Planetary Systems

Parallax Method

- **Concept**: Measures the shift in a star's position against the background when viewed from two points (e.g., six months apart in Earth's orbit).
- **Formula**:
  d=1/p , where:
  - d: Distance in parsecs (pc).
  - p: Parallax angle in arcseconds.
- **Limitation**: Effective only for nearby stars (< 1,000 parsecs).

Spectroscopic Parallax

- **Concept**: Finds distance using a star's spectrum and luminosity.
- Steps:
  1. Measure the star's apparent magnitude (m).
  2. Find its spectral type and luminosity class to estimate absolute magnitude (M).
  3. Use the distance modulus formula: m−M=5log10(d)−5 Solve for d (distance in parsecs).

Distance Modulus

- **Definition**: Relates a star's apparent and absolute magnitudes to its distance.
- Formula:
  d=10(m−M+5)/5, where:
  - d: Distance in parsecs.
  - m: Apparent magnitude (how bright the star appears from Earth).
  - M: Absolute magnitude (intrinsic brightness of the star).

Summary of Methods for Calculating Distances to Stars

1. **Parallax**
   - **Key Concept**: Measures the apparent shift in a star's position relative to the background stars when observed from different points (e.g., Earth's position six months apart).
   - **Effective Range**: Nearby stars, typically within 1,000 parsecs.
   - **Limitations**: Accuracy decreases significantly with distance due to smaller parallax angles.
2. **Spectroscopic Parallax**

- **Key Concept**: Determines distance by analyzing a star's spectrum to estimate its luminosity and absolute magnitude, then comparing it to its apparent magnitude.
    - **Effective Range**: Up to several kiloparsecs.
    - **Limitations**: Requires precise spectral measurements and assumptions about the star's classification.

3. **Distance Modulus**
    - **Key Concept**: Uses the relationship between a star's apparent magnitude (m) and absolute magnitude (M) to calculate distance with the formula: $d=10^{(m-M+5)/5}$.
    - **Effective Range**: Applicable to stars and galaxies at any distance.
    - **Limitations**: Depends on accurate measurements of apparent magnitude and proper estimation of absolute magnitude.

Advanced Topics

Gravitational Lensing:

• Light bends around massive objects, confirming Einstein's General Relativity.

Pulsars and Magnetars:

• Pulsars: Rotating neutron stars emitting radio waves.

• Magnetars: Extremely magnetic neutron stars.

Quasars and AGNs:

• Quasars: Active galactic nuclei powered by supermassive black holes.
Active galactic nuclei powered by accretion disks around black holes.

NASA Exoplanet Archive:

- Comprehensive database of all confirmed exoplanets with observation data and system parameters.

Swarthmore Transit Finder:

- Tool to find observable exoplanets based on location, date, and time.
- Features recommendations for Exoplanet Watch targets.

Sonoma State University's GORT Telescope and Las Cumbres Observatory:

- Accessible robotic telescope networks for citizen scientists and researchers.

Project PANOPTES:

- Instructions to build your own robotic telescope for exoplanet studies.

HR Diagram Overview

- **Function**: Plots a star's absolute visual magnitude (vertical axis) against its spectral class (horizontal axis).
- Developed in 1914 by Henry Norris Russell and Ejnar Hertzsprung.
- Essential for understanding star types, evolution, and transformations.

Key Features of the HR Diagram

- Spectral Classes: OBAFGKMLT (temperature scale).
    - Hotter stars (O-class): ~45,000 K, left of the diagram.
    - Cooler stars (T-class): Below 1200 K, right of the diagram.
    - Magnitude scale:
        - -10 magnitude = 1 million times brighter than the Sun.
        - +20 magnitude = 1 million times dimmer than the Sun.
- Luminosity Classes: Roman numerals indicate evolutionary states:
    - V: Main sequence (dwarfs).
    - IV: Subgiants.
    - III: Giants.
    - II: Bright giants.
    - Ib/Ia/Ia-0: Supergiants to hypergiants.
    - D: White dwarfs.

Star Evolution on the HR Diagram

- Main Sequence Stars: Fuse hydrogen into helium in their cores.
    - Lifetimes vary by mass:
        - High-mass stars (~120 solar masses): ~2 million years.
        - Low-mass stars (~0.08 solar masses): ~13 billion years.
- Post-Main Sequence Evolution:
    - Low-mass stars (<10 solar masses): Expand to giants, fuse helium, and shed outer layers, leaving white dwarfs.
    - High-mass stars (>10 solar masses): Expand as supergiants, fuse heavy elements to iron, then explode as supernovae.

Unrepresented Objects

- Planetary Nebulae: Expanding shells of gas from dying stars; central stars become white dwarfs.
- Neutron Stars: Dense (~20 km diameter, ~1 million tons/cm^3), formed after supernovae.
- Black Holes: Result from supernovae of massive stars, invisible unless accreting material.

Variable Stars on the HR Diagram

- Definition: Stars that vary in brightness due to internal or external processes.
- Types:
  - LBV (Luminous Blue Variables): Massive stars with erratic outbursts (e.g., Eta Carinae).
  - YHG (Yellow Hypergiants): Bright, semi-regular variables with dusty outbursts.
  - Cepheids: Pulsating supergiants; useful for distance measurements.
  - RR Lyrae: Low-mass helium-fusing stars; consistent luminosities.
  - Delta Scuti/Gamma Doradus: Short-period pulsating stars.
  - Mira Variables (LPV): Long-period red giants with significant brightness changes.
  - White Dwarf Variables:
    - DAV (ZZ Ceti): Hydrogen-rich, short-period pulsators.
    - DB: Helium-rich, hotter variants.
    - PG 1159: Extremely hot pre-white dwarfs.
  - Flare Stars: Sudden, violent brightness increases (e.g., Proxima Centauri).

Radial Velocity (Doppler Spectroscopy)

- How It Works: Detects exoplanets by measuring changes in the star's spectrum. As a planet orbits, it causes the star to move slightly in its own orbit. This causes a Doppler shift in the star's light (blueshift when moving toward us and redshift when moving away).
- What It Tells Us:
  - It helps calculate the minimum mass of the exoplanet (the true mass if the orbital tilt is close to 90°).
  - Works best for massive planets that are close to their stars (Hots Jupiters).
  - Size of the star's movement (the amplitude of the velocity curve) tells us about the planet's mass.
- Important Formula:

$$\frac{PK^3}{2\pi G} = \frac{(M_{e,\,\text{true}} \sin\alpha)^3}{M_s^2}$$

- Limitations:
  - Can be affected by the star's activity (like spots or oscillations).
  - Works best for large planets in close orbits.

2. Transit Method

- How It Works: The transit method measures the drop in brightness when a planet passes in front of its star (from our point of view).
  - This creates a dip in the light curve, which shows how much light is blocked by the planet.
  - We also measure how long the transit takes to get the planet's orbital period.
- What It Tells Us:
  - The transit depth gives us the radius of the exoplanet (by comparing the drop in light to the star's size).
  - Study the atmosphere using transmission spectroscopy (when light from the star passes through the planet's atmosphere during transit, and gases in the atmosphere absorb certain wavelengths of light).
- Important Formula:

$$\frac{\Delta F}{F_0} = \frac{R_p^2}{R_s^2},$$

- Key Notes:
  - For a planet to transit, its orbital inclination must be close to 90°.
  - Limb darkening: The star isn't equally bright across its surface, which affects the light curve.
  - This method works best for larger planets in close orbits with aligned orbits.

3. Direct Imaging

- How It Works: Takes pictures of exoplanets by blocking out the light from their parent star (typically done using coronagraphs).

    - Most images are taken in infrared because young planets emit more heat in this range.
- What It Tells Us:
    - We can directly measure the temperature, composition, and atmosphere of the exoplanet.
    - Especially useful for studying planet formation and young planets.
- Challenges:
    - Planets are much fainter than their stars, so getting images of them is very hard.
    - Requires advanced technology like coronagraphs or star shades to block out the star's light.
    - Best for young and large planets with wide orbits.
- Advantages:
    - Provides direct images of the planet.
    - Gives us lots of information about the planet's surface and atmosphere.

4. Temperature of Exoplanets

- The star is assumed to be a blackbody (perfect emitter of radiation).
- The exoplanet reflects some of the radiation and is assumed to have no internal heating (from its core).
- The emissivity of the exoplanet is assumed to be close to 1.

Energy Transfer from Star to Exoplanet

Using the Stefan-Boltzmann law for radiation:

$$L_s = 4\pi R_s^2 \cdot \sigma T_s^4, \qquad L_e = 4\pi R_e^2 \cdot \sigma T_e^4,$$

Where:

- σ = Stefan-Boltzmann constant

Only a fraction of the star's radiation reaches the exoplanet, and only a fraction of that is absorbed. The ratio of radiation that reaches the exoplanet is given by:

$$\frac{\pi R_e^2}{4\pi D^2}.$$

By considering the sphere centered at the sun that crosses the exoplanet, and 1-A is absorbed,

Where:

- A = Albedo of the planet

Therefore:

$$T_e^4 = \frac{R_s^2 T_s^4 (1-A)}{4D^2}, \qquad T_e = \sqrt[4]{\frac{R_s^2 T_s^4 (1-A)}{4D^2}}.$$

Greenhouse Effect

If the planet has an atmosphere with greenhouse gases, the temperature would be higher than the value predicted by this formula, due to heat trapping by the atmosphere.

Key Units in Astronomy

1. Arcminutes & Arcseconds:
    a. An arcminute is 1/60th of a degree, and an arcsecond is 1/60th of an arcminute. These units are used to measure small angles in astronomy. For example, the Moon appears to be about 1800 arcseconds across in the sky.
2. Astronomical Units (AU):
    a. 1 AU is the average distance from Earth to the Sun. It helps measure distances within our solar system.
3. Parsecs (pc):
    a. 1 parsec is the distance at which 1 AU subtends an angle of 1 arcsecond. It's used to measure distances to stars and galaxies. A kiloparsec (kpc) is 1,000 parsecs, and a megaparsec (Mpc) is 1 million parsecs.
4. Light Years (ly):
    a. A light year is the distance that light travels in one year. It's often used for measuring long distances, such as to stars or galaxies. There are also smaller units like light minutes or light seconds for shorter distances.
5. Solar Units:
    a. The solar mass is the mass of the Sun, and the solar radius is the radius of the Sun. The solar luminosity is the total energy the Sun radiates per second, and the solar effective temperature is the temperature of a blackbody that emits the same amount of light as the Sun.
6. Angstrom:

a. 1 Angstrom is 1/10th of a nanometer or 10^-10 meters. It is used in astronomy to measure wavelengths, especially in the study of light from stars and other objects.

Kepler's Laws of Planetary Motion

Kepler's First Law (Elliptical Orbits)

- Kepler's first law states that planets move in elliptical orbits with the Sun at one of the foci, not at the center. This means that the distance between a planet and the Sun changes as the planet moves along its orbit.
- The semi-major axis of an orbit is half the longest diameter of the ellipse, and the semi-minor axis is half the shortest. The eccentricity of the orbit describes how stretched out the ellipse is. A circle is a special case of an ellipse where the eccentricity is 0.
- The closest point to the Sun in a planet's orbit is called periapsis (or perihelion if it's around the Sun), and the farthest point is called apoapsis (or aphelion if it's around the Sun).

Kepler's Second Law (Equal Areas in Equal Times)

- Kepler's second law states that a planet sweeps out equal areas in equal times as it orbits the Sun. This means planets move faster when they're closer to the Sun and slower when they're farther away. The closer the planet is, the more area it covers in the same amount of time.

Summary of Key Concepts

- Orbital Motion: The movement of planets and satellites follows Kepler's laws, which describe how objects orbit in elliptical paths around a central body, like the Sun.
- Unit Conversions: In astronomy, understanding units like AU, parsecs, and light years is essential for measuring distances. For small angles, arcminutes and arcseconds are commonly used.

PART 3

The Orion Nebula

- **Location**: The Orion Nebula is located in the constellation Orion, beneath the three stars forming Orion's Belt, the “middle star” in Orion's Sword, part of the Orion Molecular Cloud (OMC)
- **Distance from Earth**: Approximately 1,344 light-years (412.1 parsecs).
- **Apparent Magnitude**: +4.0 (visible to the naked eye under dark skies).
- **Size**: About 24 light-years across, with a visible portion of about 1° across the sky.
- **Mass:** 2000 times that of the Sun
- **Other Names:** Great Nebula or Great Orion Nebula
- **Type**: Diffuse nebula and H II region (a region of ionized hydrogen gas).
- **Gas and Dust**:
  - Primarily composed of hydrogen (ionized H II and neutral H I).
  - Includes helium, oxygen, nitrogen, sulfur, and other trace elements.
  - Dust grains scatter and absorb light, creating darker regions.
- **Regions**:
  - **Trapezium Cluster**: A group of four massive, young stars at the nebula's core, responsible for ionizing the surrounding gas.
  - **Bright and Dark Areas**: Bright emission regions are due to ionized gas illuminated by ultraviolet radiation from the Trapezium stars, while dark areas contain dense molecular clouds obscuring light.
- **Molecular Cloud**:
  - The Orion Nebula is part of the larger Orion Molecular Cloud Complex, which includes other notable star-forming regions such as Barnard's Loop and the Horsehead Nebula.
  - Contains dense regions where gas and dust collapse under gravity to form protostars.
- **Stellar Formation**:
  - Protostars in the nebula emit jets that interact with surrounding material, creating features like Herbig-Haro objects.
  - Massive young stars, like those in the Trapezium Cluster, form from collapsing material in molecular clouds.
- **Stellar Evolution**:
  - **Protostars**: Many protostars are observed within the nebula, indicating the early stages of star formation.
  - **T Tauri Stars**: Pre-main-sequence stars that exhibit variability and strong stellar winds.
  - **Protoplanetary Disks**: Observed around young stars; these disks are precursors to planetary systems.
- **Ionization**: Ultraviolet light from the Trapezium stars ionizes surrounding hydrogen gas, causing it to emit visible light (H-alpha line).

- **Emission Lines**: Spectral lines from oxygen ([O III]), sulfur ([S II]), and nitrogen ([N II]) are prominent in the nebula.
- **Reflection**: Some areas reflect light from nearby stars, creating a blueish hue.
- **Exoplanetary Disk Observation**:
  - Over 150 protoplanetary disks (proplyds) have been identified, indicating sites of potential planet formation.
- **Orion Nebula Cluster (ONC)**: The young open star cluster within the nebula contains over 2,000 stars.
- **Bow Shocks**: Created by high-speed stellar winds colliding with surrounding gas.
- **Outflows and Jets**: Caused by protostellar winds, shaping the nebula's morphology.
- **Discovery**:
  - Known since antiquity, it was first described telescopically by Nicolas-Claude Fabri de Peiresc in 1610.
  - Cataloged by Charles Messier in 1769 as M42.
- **Best Time to Observe:** Winter months (December to February) in the Northern Hemisphere.
- **Equipment**:
  - Visible to the naked eye under dark skies.
  - Binoculars or telescopes reveal intricate details, including the Trapezium Cluster and nebulosity.
- **Wavelengths**:
  - Optical: Shows bright emission and dark dust lanes.
  - Infrared: Penetrates dust to reveal embedded stars and protoplanetary disks.

30 Doradus (Tarantula Nebula)

- **Location**: In the constellation Dorado, located in the Large Magellanic Cloud (LMC), a satellite galaxy of the Milky Way.
- **Distance from Earth**: Approximately 160,000 light-years (49 kiloparsecs).
- **Apparent Magnitude**: About +8.0, visible with binoculars or small telescopes in the Southern Hemisphere.
- **Size**: About 1,000 light-years across, making it the largest and most active star-forming region in the Local Group of galaxies.
- **Type**: Giant H II region, characterized by ionized hydrogen gas illuminated by massive young stars.
- **Gas and Dust**:
  - Primarily hydrogen, with traces of helium and heavier elements.
  - Contains both dense molecular clouds and less-dense ionized gas.
- **Regions**:

    - **Central R136 Cluster**: A dense, massive stellar cluster containing some of the most massive stars known.
    - Surrounding filaments and knots of gas and dust form the "legs" of the Tarantula Nebula, giving it its spider-like appearance.
- **Active Star Formation**:
    - One of the most intense star-forming regions in the universe.
    - Gas and dust collapse under gravity to form stars, with the influence of feedback mechanisms from massive stars.
- **R136 Cluster**:
    - Contains stars with masses exceeding 100 solar masses, including some of the most luminous and massive stars ever observed, such as **R136a1**.
    - The cluster is only a few million years old, highlighting massive stars' rapid formation and evolution.
- **Protostars** and **Protoplanetary Disks**:
    - Early-stage stellar objects and disks of material around young stars are present, indicating active stellar and planetary formation.
- **Ionization**:
    - Intense ultraviolet radiation from massive stars in R136 ionizes surrounding hydrogen gas, causing it to emit light in the visible spectrum (notably H-alpha).
- **Spectral Lines**:
    - Prominent emission lines from elements like oxygen ([O III]), nitrogen ([N II]), and sulfur ([S II]) dominate the nebula's spectrum.
- **X-Ray Emission**:
    - High-energy X-rays are generated by stellar winds from massive stars and their collisions.
- **Massive Stars**:
    - Includes Wolf-Rayet stars and O-type stars that will evolve into supernovae.
    - These stars have short lifespans and high luminosities
- **Supernova Remnants**:
    - The nebula contains remnants of past supernovae, contributing to its enrichment with heavier elements.
- **N132D**: A supernova remnant located within the nebula.
- **Feedback Effects**:
    - Supernovae and stellar winds shape the surrounding nebula by compressing gas to trigger new star formation or dispersing it to inhibit further formation.
- **Elemental Enrichment**:
    - Heavy elements released by massive stars enrich the surrounding interstellar medium.
- **Comparison to the Milky Way**:
    - Has star formation in conditions not present in the Milky Way.

- **Massive Stellar Winds**:
    - Winds from stars in R136 carve cavities and produce bow shocks within the gas.
- **Filaments and Pillars**:
    - Dense filaments and pillars of gas are shaped by radiation pressure and winds
- **Optical**:
    - Visible features include ionized gas and young stars.
- **Infrared**:
    - Reveals protostars and deeply embedded star-forming regions.
- **X-Ray**:
    - Highlights energetic processes, including collisions of stellar winds and supernova remnants.
- **Radio**:
    - Probes cooler, denser regions of gas.
- **Discovery**:
    - Known since early observations of the Large Magellanic Cloud.
    - Named the "Tarantula Nebula" due to its appearance in wide-field images.
- **Best Time**: Visible year-round in the Southern Hemisphere; best observed during Southern Hemisphere summer.
- **Equipment**:
    - Binoculars or small telescopes reveal the brightest parts.
    - Large telescopes resolve the central R136 cluster and surrounding filaments.

HD 80606b

- **Host Star**: HD 80606
    - **Type**: G5V star (similar to the Sun but slightly cooler).
    - **Location**: Approximately 217 light-years away in the constellation **Ursa Major**.
    - **Apparent Magnitude**: +9.0 (not visible to the naked eye; requires a telescope).
- **Planetary System**:
    - **HD 80606b** is the only confirmed planet in the system.
    - Discovery Year: 2001 via the radial velocity method.
- **Orbit**:
    - **Highly Eccentric**: One of the most eccentric orbits observed for an exoplanet (e=0.93e = 0.93e=0.93), comparable to Halley's Comet
        - Closest Approach (Periastron): 0.03 AU (closer than Mercury is to the Sun).
        - Farthest Distance (Apastron): 0.88 AU (near the orbit of Venus).
    - Orbital Period: ~111.4 Earth days.
- **Orbital Dynamics**:

    - HD 80606b's extreme orbit suggests a history of gravitational interactions, possibly with a now-lost companion star or planet.
    - Kozai-Lidov oscillations, caused by interactions with a distant stellar companion (HD 80607), may have shaped its eccentricity.
- **Type**: Gas giant (similar to Jupiter).
- **Mass**: ~4 Jupiter masses.
- **Radius**: Comparable to Jupiter.
- **Density**: High density due to its mass, indicating a gas giant with a substantial core.
- **Temperature**:
    - Extreme temperature variations due to its eccentric orbit:
        - At periastron: Temperatures soar to over 1,500 K as it absorbs intense radiation.
        - At apastron: Temperatures drop significantly, below 500 K, as it moves far from the host star.
- **Atmospheric Dynamics**:
    - Rapid heating and cooling during its orbit cause severe atmospheric turbulence.
    - Observations suggest strong winds and shock waves as the atmosphere reacts to sudden heating.
- **Transit Observation**:
    - HD 80606b transits its host star during certain orbital alignments
    - Transit duration is unusually short due to its high velocity at periastron.
- **Secondary Eclipse**:
    - Observations of the planet passing behind the star provide direct measurements of its emitted and reflected light, offering insights into its atmospheric temperature and composition.
- **Extreme Eccentricity**:
    - The planet's orbit challenges traditional models of planetary system formation and evolution.
    - Highlights the impact of gravitational interactions on planetary orbits.
- **Atmospheric Dynamics**:
    - Serves as a natural laboratory for studying atmospheric physics under extreme conditions.
    - Helps refine models of heat redistribution and thermal inertia in exoplanet atmospheres.
- **Habitability Considerations**:
    - The extreme orbit makes HD 80606b inhospitable for life as we know it, but it provides insights into the boundaries of planetary habitability.

WASP-17b

- **Host Star**: WASP-17
  - **Type**: F6V (slightly hotter and more massive than the Sun).
  - **Location**: Approximately 1,300 light-years (400 parsecs) away in the constellation **Scorpius**.
  - **Apparent Magnitude**: ~11.6 (requires a telescope to observe).
  - **Size and Mass:** one of the largest exoplanets ever discovered at double the size of Jupiter yet half of Jupiter's mass; "puffy" planet
- **Discovery**:
  - Detected in 2009 by the **Wide Angle Search for Planets (WASP)** project.
  - Discovery Method: **Transit method**, where the planet passes in front of its star, causing a dip in brightness.
- **Orbit**:
  - **Semi-Major Axis**: ~0.05 AU (about 1/10th the distance between Mercury and the Sun).
  - **Orbital Period**: ~3.7 Earth days (a "hot Jupiter" with a close-in orbit).
  - **Eccentricity**: Near circular ($e \approx 0$), likely due to tidal interactions with the host star.
- **Retrograde Orbit**:
  - WASP-17b orbits in the opposite direction of its star's rotation, a rare and intriguing phenomenon.
  - Likely caused by a gravitational interaction (e.g., with another planet or star) that altered its orbit after formation.
- **Type**: Gas giant (Hot Jupiter).
- **Mass**: ~0.49 Jupiter masses (less than half the mass of Jupiter).
- **Radius**: ~1.99 Jupiter radii (nearly twice the size of Jupiter).
- **Density**: ~0.06 g/cm^3 (extremely low, about the density of expanded polystyrene foam).
  - The low density makes WASP-17b one of the "puffiest" known exoplanets.
- **Temperature**:
  - Estimated to range between 1,300–1,500 K due to its proximity to the host star.
  - Classified as a "hot Jupiter" with a strongly irradiated atmosphere.
- **Composition**:
  - Likely dominated by hydrogen and helium with trace amounts of heavier elements.
  - Observations suggest possible molecular features such as water vapor, carbon dioxide, and methane.
- **Clouds and Hazes**:
  - The planet's atmosphere may contain clouds of silicates or metallic compounds and hazes that scatter light.
- **Atmospheric Escape**:

    - Due to its low density and high temperature, WASP-17b may be experiencing atmospheric escape, where lighter gases are lost to space.
- **Inflated Atmosphere**:
    - The planet's low density and large radius suggest significant atmospheric inflation, likely caused by intense stellar irradiation, tidal heating, or other mechanisms.
    - Helps refine models of planetary structure and thermal evolution.

WASP-121b

- **Host Star**: WASP-121
    - **Type**: F6V (slightly hotter and more massive than the Sun).
    - **Location**: Approximately 850 light-years (260 parsecs) away in the constellation **Puppis**.
    - **Apparent Magnitude**: ~10.4 (requires a telescope for observation).
- **Discovery**:
    - Detected in 2015 by the **Wide Angle Search for Planets (WASP)** project.
    - Discovery Method: **Transit method**, where periodic dips in the star's brightness indicate the presence of an orbiting planet.
- **Orbit**:
    - **Semi-Major Axis**: ~0.025 AU (extremely close to its host star; about 1/20th the distance of Mercury to the Sun).
    - **Orbital Period**: ~1.27 Earth days (extremely short, completing an orbit in ~30 hours).
    - **Eccentricity**: Nearly circular ($e \approx 0$), likely due to tidal interactions with the host star.
- **Tidal Locking**:
    - WASP-121b is tidally locked, meaning one side (the day side) is perpetually facing the star, while the other side (the night side) remains in darkness.
    - This creates a stark temperature gradient between the two hemispheres.
- **Type**: Gas giant (Hot Jupiter).
- **Mass**: ~1.18 Jupiter masses.
- **Radius**: ~1.81 Jupiter radii (inflated due to stellar heating).
- **Density**: ~0.33 g/cm^3 (much lower than Jupiter, indicating a "puffed-up" atmosphere).
- **Temperature**:
    - Day Side: ~2,500–3,000 K, making it one of the hottest exoplanets observed.
    - Night Side: Much cooler but still significantly warm compared to Earth.
- **Composition**:

    - In its atmosphere, Spectroscopy has detected water vapor, carbon monoxide, and metal ions (e.g., magnesium and iron).
    - Observations also suggest the presence of vanadium oxide (VO) and titanium oxide (TiO), which can act as high-temperature "sunscreens" by absorbing stellar radiation.
- **Stratosphere**:
    - Evidence of a temperature inversion caused by absorption of high-energy radiation by metal oxides in the upper atmosphere.
- **Atmospheric Escape**:
    - WASP-121b is so close to its host star that its outer atmosphere is stripped away, forming a comet-like tail of escaping material.
    - This phenomenon is driven by extreme stellar radiation.
- **Weather and Winds**:
    - Supersonic winds likely transport heat from the day side to the night side.
    - The night side may host cloud formations, potentially made of exotic materials like metal sulfides.

LTT 9779b

- **Host Star**: LTT 9779
    - **Type**: G8V (slightly cooler and smaller than the Sun).
    - **Location**: Approximately 260 light-years (80 parsecs) away in the constellation **Sculptor**.
    - **Apparent Magnitude**: ~9.8 (requires a telescope to observe).
- **Discovery**:
    - Found in 2020 by NASA's **Transiting Exoplanet Survey Satellite (TESS)** mission.
    - Detection Method: **Transit method**, where the planet passes in front of its star, causing a periodic dip in brightness.
- **Orbit**:
    - **Semi-Major Axis**: ~0.016 AU (extremely close to its host star, about 1/6th the distance of Mercury to the Sun).
    - **Orbital Period**: ~0.79 Earth days (just under 19 hours, making it a very short-period planet).
    - **Eccentricity**: Near circular (e≈0e $\approx$ 0e≈0) due to strong tidal forces from the host star.
- **Tidal Locking**:
    - LTT 9779b is tidally locked, with one side (the day side) always facing the star and the other (the night side) perpetually in darkness.

    - This creates significant temperature contrasts between hemispheres.
- **Type**: Ultra-hot Neptune (a Neptune-like planet subjected to extreme stellar radiation).
- **Mass**: ~29 Earth masses (comparable to Neptune, which is ~17 Earth masses).
- **Radius**: ~4.7 Earth radii.
- **Density**: ~1.3 g/cm^3, indicating a gaseous envelope surrounding a rocky or metallic core.
- **Reflectivity:** albedo of 0.8, making it very reflective
- **Temperature**:
    - Day Side: ~2,000 K due to extreme proximity to the host star.
    - Night Side: Significantly cooler but still hot, highlighting the challenges of heat redistribution.
- **Composition**:
    - Observations have identified water vapor and evidence of heavy metals like titanium and iron in its atmosphere.
    - High temperatures may lead to the presence of molecular dissociation and ionization.
- **Atmospheric Escape**:
    - The intense stellar radiation is causing the planet to lose its atmosphere over time, a phenomenon known as **atmospheric stripping**.
    - Despite this, LTT 9779b has retained a substantial atmosphere, which is surprising given its extreme environment.
- **Clouds and Hazes**:
    - The planet's atmosphere likely contains silicate clouds or metallic hazes due to high temperatures, especially on the night side.

GJ 1214b

- **Host Star**: GJ 1214
    - **Type**: M4.5V (red dwarf, smaller and cooler than the Sun).
    - **Location**: Approximately 40 light-years (12.9 parsecs) away in the constellation **Ophiuchus**.
    - **Apparent Magnitude**: ~14.7 (requires a large telescope to observe).
    - **Luminosity**: ~0.003 times that of the Sun, making it a dim star.
- **Discovery**:
    - Detected in 2009 by the MEarth Project, a ground-based survey for transiting exoplanets around M-dwarf stars.
    - Discovery Method: **Transit method**, observing periodic dips in the star's brightness as the planet passes in front of it.
- **Orbit**:

- **Semi-Major Axis**: ~0.014 AU (about 2% the Earth-Sun distance, closer than Mercury is to the Sun).
- **Orbital Period**: ~1.58 Earth days (completes an orbit in less than 2 days).
- **Eccentricity**: Near circular ($e \approx 0$), likely due to tidal forces from the host star.

- **Tidal Locking**:
  - GJ 1214b is tidally locked, meaning one side (the day side) constantly faces the star, while the other (the night side) remains in perpetual darkness.
- **Type**: Sub-Neptune or Mini-Neptune.
- **Mass**: ~6.26 Earth masses.
- **Radius**: ~2.68 Earth radii.
- **Density**: ~1.87 g/cm^3, suggesting a composition of a thick atmosphere overlying a solid or liquid interior.
- **Temperature**:
  - Estimated equilibrium temperature: ~400–500 K (depending on albedo and atmospheric properties).
- **Composition**:
  - The atmosphere likely consists of hydrogen and helium, with possible contributions from water vapor, methane, or other molecules.
  - Observations indicate a high-altitude haze or thick cloud layer obscuring detailed spectral features.
- **Clouds and Hazes**:
  - The planet's atmosphere is dominated by hazes or clouds, potentially made of water, methane, or hydrocarbon compounds.
- **Atmospheric Retention**:
  - GJ 1214b's mass and proximity to its star allow it to retain a substantial atmosphere despite stellar irradiation.

K2-18b

- **Host Star**: K2-18
  - **Type**: M3V (red dwarf, smaller, cooler, and dimmer than the Sun).
  - **Location**: Approximately 124 light-years (38 parsecs) away in the constellation **Leo**.
  - **Apparent Magnitude**: ~13.5 (requires a telescope to observe).
  - **Luminosity**: ~0.023 times that of the Sun, making it much dimmer than our star.
- **Discovery**:
  - Found in 2015 during NASA's **K2 Mission** (the extended Kepler mission).
  - Discovery Method: **Transit method**, where the planet periodically blocks a small fraction of the star's light.

- **Orbit**:
  - **Semi-Major Axis**: ~0.1429 AU (just under half the distance of Mercury from the Sun).
  - **Orbital Period**: ~33 Earth days, placing it in the star's habitable zone.
  - **Eccentricity**: Near circular (e≈0e ≈ 0e≈0), likely stabilized by tidal interactions.
- **Habitable Zone**:
  - The planet's orbit allows it to receive stellar radiation levels conducive to liquid water, depending on its atmosphere.
- **Type**: Mini-Neptune or Sub-Neptune.
- **Mass**: ~8.92 Earth masses.
- **Radius**: ~2.6 Earth radii.
- **Density**: ~3.7 g/cm^3, indicating it likely has a solid core surrounded by a thick gaseous envelope.
- **Classification**:
  - Positioned at the boundary between rocky super-Earths and gaseous Neptune-like planets, making it a key object for studying planetary evolution.
- **Temperature**:
  - Equilibrium temperature: ~265 K (similar to Earth's global average temperature), assuming Earth-like reflectivity (albedo).
- **Composition**:
  - Observations suggest the presence of water vapor in its atmosphere, making it the first habitable-zone planet to show such a feature.
  - Hydrogen and helium dominate the atmosphere, with traces of heavier molecules such as water and methane.
- **Clouds and Hazes**:
  - Clouds or hazes may obscure parts of the atmosphere, affecting spectral observations.
  - The presence of water clouds is plausible at certain altitudes and temperatures.
- **Habitability**:
  - K2-18b's atmosphere is likely too thick and dense for Earth-like surface conditions. However, regions within its atmosphere at certain pressures and temperatures may be more hospitable.

TOI- 270b

https://science.nasa.gov/exoplanet-catalog/toi-270-b/

- A super Earth exoplanet that orbits an M-type star
  - Mass is 1.58 Earths
  - takes about 2.4 days to orbit (orbit radius 0.03197)
  - Discovered in 2019
- https://exoplanet.eu/catalog/toi_270_b--7048/ more info on the specific things of this object

LHS 3844b

https://science.nasa.gov/exoplanet-catalog/lhs-3844-b/

- Rocky super earth-sized exoplanet that orbits red dwarf star in Indus constellation
    - Discovered in 2018 using Transiting Exoplanet Survey Satellite (TESS)
    - Planet radius 1.303 x Earth
    - Orbital period is 0.5 days which is half a day
    - 49 light years away from earth
    - Most likely "tidally locked" with one side of the plant permanently facing the star

PRS B 1257+12

https://science.nasa.gov/exoplanet-catalog/psr-b125712-b/

- Undead star known as a pulsar
- 0.338 x Earth and terrestrial planet
- Discovered 1994
- Orbital period 25.3 days
- Mass is 0.02 earths and orbital radius is 0.19 AU

WD 1856+534

https://science.nasa.gov/exoplanet-catalog/wd-1856534-b/

- 81 light years away
- A gas giant exoplanet orbiting a K-type star
- Mass is 13.8 Jupiters
- 1.4 days to complete one orbit around its star
- 0.0204 AU
- Found in 2020
- https://exoplanet.eu/catalog/wd_1856_534_b--7277/

55 Cancri e

https://science.nasa.gov/exoplanet-catalog/55-cancri-e/

- 41 light years away from earth
- Planet radius is 1.875 x Earth
- A super earth and is extremely hot (reaching 4,400 F)

Kepler-62

https://www.nasa.gov/image-article/kepler-62-solar-system/

- A 5 planet solar system about 1200 light years away from Earth in constellation Lyra
    - All stars orbit a star called a K2 dwarf (measuring two thirds of the size of the sun)

- This is a home to two habitable zone worlds making it smallest exoplanet known in the habitable zone of another star
- Planets are named with b, c, d ,e, f
- https://exoplanetarchive.ipac.caltech.edu/overview/Kepler-62/

AU Microscopii
https://science.nasa.gov/exoplanet-catalog/au-microscopii-b/

- 32 light years away
- Young planet blasted by its angry young stars
  - Very green and has a faint ring around it
  - Among the youngest planetary systems ever observed by astronomers
  - 8.5 days orbital period
  - The mass is 20.12 earths
  - It's very neptune like
  - The color appears green to the naked eye but its just because the planets activity
    - The light output is in rich in short waves which are blue and greenish colors which contributes to the color

Epsilon Eridani
http://stars.astro.illinois.edu/sow/epseri.html
https://www.astronomy.com/science/epsilon-eridani/

- 10.5 light years away from earth
- The third closest naked eye star
  - Very similar to young sun and its location to research how planets form around sunlike stars

1. Stellar Classification

- **Spectral Types**: O, B, A, F, G, K, M (hottest to coolest)
  - **Mnemonic**: *Oh Be A Fine Girl/Guy, Kiss Me*
- **Luminosity Classes**: I (supergiant), III (giant), V (main-sequence)

2. Spectral Features & Chemical Composition

- Absorption lines help determine **temperature**, **composition**, and **motion**.
- Heavier elements appear in older stars due to nucleosynthesis.
- Balmer lines (H-alpha, H-beta, etc.) are prominent in A-type stars.

3. Luminosity & Blackbody Radiation

- **Stefan-Boltzmann Law**: L=4πR2σT4L = 4\pi R^2 \sigma T^4L=4πR2σT4

- **Wien's Law**: λmax=bT\lambda_{\text{max}} = \frac{b}{T}λmax=Tb (Color relates to temp)

4. Color Index

- B−VB-VB−V value: hotter stars = lower (bluer), cooler stars = higher (redder)
- Color index used to approximate **temperature**

5. H-R Diagram Transitions

- **Main sequence** → Red Giant/Supergiant → White Dwarf/Neutron Star/Black Hole
- Life track depends on **initial mass**.

6. Interstellar Medium & Early Star Formation

- **Molecular Clouds**: Cold, dense gas; birthplace of stars.
- **HI regions**: Neutral hydrogen; detected via 21 cm line.
- **HII regions**: Ionized hydrogen from young, hot stars.

7. Protostars & Young Stellar Objects

- **Protostar**: Gravitational collapse but not yet fusing H.
- **Herbig-Haro (HH) Objects**: Emission from jets in YSOs colliding with gas.
- **T Tauri Variables**: $<2\ M_\odot$, strong magnetic fields, accretion disks.
- **Herbig Ae/Be Stars**: 2–8 $M_\odot$ pre-main sequence stars.

8. Planet Formation

- **Protoplanetary Disks**: Dust/gas disks that form planets.
- **Debris Disks**: Remnants of planet formation; contain asteroids/comets.
- **Brown Dwarfs**: Substellar, no sustained hydrogen fusion, mass $< 0.08\ M_\odot$.

9. Exoplanets

- **Gas Giants**: Massive, mostly H/He (e.g., Jupiter-like)
- **Terrestrial**: Rocky, smaller, closer to the star
- May form through **core accretion** or **disk instability**

Section B: Mechanics, Detection, and Habitability

1. Orbital Mechanics

- **Kepler's Laws**:
  - Elliptical orbits
  - Equal areas in equal times
  - P2∝a3P^2 \propto a^3P2∝a3
- **Circular Motion**:
  - Centripetal force: F=mv2rF = \frac{mv^2}{r}F=rmv2
  - Orbital velocity: v=GMrv = \sqrt{\frac{GM}{r}}v=rGM

1. Star Formation Regions

- **Carina Nebula (NGC 3372)**:

  - A massive star-forming complex visible from the southern hemisphere.
  - Contains both **emission nebulae** (red regions emitting radiation) and **reflection nebulae** (blue regions reflecting UV radiation from nearby massive stars).
  - Home to dense molecular clouds and dark absorption nebulae, serving as stellar nurseries.
- **NGC 1333**:

  - A reflection nebula located in the Perseus constellation.
  - Rich in young stars and protostellar objects, making it an active star-forming region.

2. Protostars and Young Stellar Objects (YSOs)

- **Bok Globules**:

  - Small, dense, dark clouds of gas and dust within molecular clouds.
  - Potential sites for star formation if they accumulate sufficient mass to collapse under gravity.
- **Herbig-Haro (HH) Objects**:

  - Bright patches of nebulosity associated with newborn stars.
  - Formed when jets ejected by protostars collide with surrounding gas and dust at high speeds.
  - **Example**: **HH 7–11** in NGC 1333, showcasing multiple HH objects in close proximity.
- **T Tauri Stars**:

  - Young, pre-main-sequence stars less than 2 solar masses.
  - Characterized by variability in brightness and strong stellar winds.

    - Often surrounded by circumstellar disks, potential sites for planet formation.
- **Herbig Ae/Be Stars**:
    - Intermediate-mass pre-main-sequence stars (2–8 solar masses).
    - Exhibit emission lines in their spectra and are often associated with reflection nebulae.
    - Serve as a bridge between low-mass T Tauri stars and high-mass main-sequence stars.

3. Brown Dwarfs and Substellar Objects

- **Brown Dwarfs**:
    - Objects with masses between the heaviest gas giant planets and the lightest stars (~13–80 Jupiter masses).
    - Do not sustain hydrogen fusion in their cores.
    - **Example**: **Luhman 16**, a binary brown dwarf system located approximately 6.5 light-years away.

4. Protoplanetary and Debris Disks

- **Protoplanetary Disks**:
    - Disks of gas and dust surrounding young stars, sites of planet formation.
    - **Example**: **HD 169142**, a young star with a well-studied protoplanetary disk showing gaps that may indicate forming planets.
- **Debris Disks**:
    - Dusty disks around stars, composed of remnants from planet formation processes.
    - **Example**: **Beta Pictoris**, a star with a prominent debris disk and at least two known exoplanets.

5. Exoplanets

- **Detection Methods**:
    - **Radial Velocity**: Measures star's wobble due to gravitational pull of orbiting planets.
    - **Transit Photometry**: Detects dips in stellar brightness as planets pass in front of their host stars.
    - **Direct Imaging**: Captures images of exoplanets by blocking out starlight.

- **Notable Exoplanets**:
  - **WASP-18b**: A massive hot Jupiter with an orbital period of less than one day.
  - **WASP-39b**: A Saturn-mass exoplanet known for its bloated atmosphere, recently studied by the James Webb Space Telescope.
  - **TRAPPIST-1 System**: Contains seven Earth-sized planets, with three in the habitable zone.

Section B: Mechanics, Detection, and Habitability

1. Orbital Mechanics and Kepler's Laws

- **Kepler's Third Law**:
  - P2=a3P^2 = a^3P2=a3 (for objects orbiting the Sun), where PPP is the orbital period in years and aaa is the semi-major axis in astronomical units (AU).

2. Distance Measurement Techniques

- **Parallax**:
  - d=1pd = \frac{1}{p}d=p1, where ppp is the parallax angle in arcseconds, and ddd is the distance in parsecs.
- **Spectroscopic Parallax**:
  - Determines distance by comparing a star's apparent magnitude with its absolute magnitude, inferred from its spectral type.
- **Distance Modulus**:
  - m−M=5log10(d)−5m - M = 5 \log_{10}(d) - 5m−M=5log10(d)−5, where mmm is the apparent magnitude, M is the absolute magnitude, and d is the distance in parsecs.

3. Exoplanet Detection Techniques

- **Radial Velocity Method**:
  - Detects variations in the velocity of a star due to gravitational tugs from orbiting planets, observed as Doppler shifts in the star's spectral lines.
- **Transit Photometry Method**:

    - Measures the dimming of a star's light when a planet transits (passes in front of) the star, providing planet size and orbital information.
- **Direct Imaging**:
    - Captures actual images of exoplanets by blocking out the host star's light, often using coronagraphs or starshades.

4. Radiation Laws and Habitability

- **Stefan-Boltzmann Law**:
    - L=4πR2σT4L = 4\pi R^2 \sigma T^4L=4πR2σT4, relating a star's luminosity (LLL) to its radius (RRR) and surface temperature (TTT).
- **Wien’s Displacement Law**:
    - λmax=bT\lambda_{\text{max}} = \frac{b}{T}λmax=Tb, indicating the peak wavelength (λmax\lambda_{\text{max}}λmax) of a blackbody spectrum shifts inversely with temperature.
- **Habitable Zone**:
    - The region around a star where conditions might be right for liquid water to exist on a planet's surface, often termed the "Goldilocks Zone."

Section C: Deep Sky Objects (DSOs) and Systems

Object/System	Description
Carina Nebula (NGC 3372)	Massive star-forming region with both emission and reflection nebulae.
NGC 1333	Reflection nebula with active star formation and numerous protostars.
TW Hydrae (TW Hya)	Closest T Tauri star with a well-studied protoplanetary disk.
HH 7–11	Group of Herbig-Haro objects in NGC 1333, indicating active star formation.
AB Aurigae (AB Aur)	Herbig Ae star with a complex protoplanetary disk

SLIDES INFO

Slide 5: Carina Nebula (NGC 3382)

- **Type**: Massive star formation complex (southern sky)
- **Components**:
    - **Emission Nebula** (Red): Heated enough to emit radiation
    - **Reflection Nebula** (Blue): Reflects UV radiation from massive stars
    - **Absorption Nebula** (Dark): Molecular clouds absorbing background light
- **Image link**: Carina - Hubble

Slide 6: Molecular Clouds

- **Traits**: Cold, dense, irregular gas clouds (contain H_2 molecules)
- **Star Formation Role**: UV radiation from young massive stars ionizes gas
- **Forms**:
    - HII regions: Emission Nebulae (red)
    - Reflection Nebulae (blue)
- **Image**: Molecular Cloud - ESA

Slide 7: Bok Globules

- **Definition**: Dense, dark cloud clumps that can form protostars
- **Relevance**: Often seen in early star formation; form from non-eroded molecular clouds
- **Example Image**: The "Caterpillar" Bok globule – ESA Hubble

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Slide 8: Protostar Formation Image

- **Image Content**: Massive, active star formation region
- **Processes**: Protostar jets, accretion, and erosion by photoionization
- **Scale**: ~3 light-years across
- **Links**:
    - Hubble Image
    - JWST Article

Slide 9: Radiation Wavelengths in Star Formation

- **Example**: Eagle Nebula (not in Carina)
- **Purpose**: Shows multi-wavelength emission from star formation
- **Activity Link**: Interactive - Eagle Nebula

Slide 10: NGC 1333

- **Type**: Reflection Nebula
- **Distance**: ~1,000 light-years
- **Features**:
  - Blue scattered light from young stars
  - Red HH object emissions (jets, shocks)
  - Hundreds of young stars (<1 million years)
- **Image Link**: NGC 1333 - Hubble

Slide 11A: Hertzsprung-Russell (H-R) Diagram

- **Axes**:
  - X-axis: Stellar Classification / Temperature
  - Y-axis: Absolute Magnitude / Luminosity
- **Sun's Location**: G2 type, ~6000K, 1 solar luminosity
- **Use**: Determines star's age, mass, composition, and evolution stage
- **Links**:
  - Stellar Evolution Guide
  - HR Diagram Tool

Slide 11B: T Tauri & Herbig Ae/Be Stars

- **T Tauri**:
  - <2 solar masses, young, pre-main sequence
  - Found to the right of main sequence on H-R diagram
- **Herbig Ae/Be**:
  - 2–8 solar masses, pre-main sequence
- **>8 Solar Mass Stars**:
  - Not observable in this stage — evolve too quickly

- **Links**: Same Chandra links as above

SCIOLY WIKI

Stellar Life Cycle

Supernovae

A **supernova** is an event where a star explodes, destroying itself and releasing huge amounts of energy. It is distinct from a **nova**, which is a smaller explosion that does not destroy the progenitor star. Depending on the star's mass, the supernova may leave behind a neutron star or a black hole.

Type Ia supernovae are caused not by high-mass stars reaching the end of their lives, but by white dwarves that gain too much mass. They generally occur in binary systems in which a white dwarf pulls enough mass off of its companion to go supernova, or when two white dwarfs collide with each other. Either way, the white dwarf exceeds the *Chandrasekhar limit* (1.4 solar masses), and blows itself up in a supernova that is significantly brighter than a Type II supernova. They are distinguished from other type I supernovae by the presence of a strong silicon absorption line in their spectra. All Type Ia supernovae are of essentially the same brightness, and this fact can be used to determine intergalactic distances.

Type II supernovae occur when a star of at least eight solar masses cannot fuse any more elements together to create energy. This happens when iron is created; no nuclear energy can be made from iron with fusion or fission. When this happens, the star blows itself apart. Heavy elements - elements with atomic numbers greater than 26 - are created in these supernovae. If the star's core has a mass of 1.4 to 3.2 solar masses, a **neutron star** is formed. Neutron stars are incredibly dense - a neutron star with a diameter of about 12 km has the same mass as the Sun. Some neutron stars rotate quickly enough to emit beams of radiation at the magnetic poles; these are called **pulsars**, as the beams appear to "pulse" at a constant rate. However, if the core has a mass greater than 3.2 solar masses, a **black hole** is formed, which are mysterious objects described by Einstein's theory of General Relativity. Their gravity is so great that at a certain distance, called the **event horizon**, not even light can escape. This is where they get the name "black" holes.

Type Ib and **type Ic** supernovae occur via the same core-collapse mechanism as type II supernovae, but originate from stars that have lost their hydrogen envelopes. Like type Ia supernovae, they are characterized by a lack of hydrogen absorption lines in their spectra; type Ic supernovae also lack helium absorption lines.

Stellar Classification

Stars are classified in many ways. The two most common methods are discussed here.

Spectral Class

First, stars can be categorized through Spectral Class (Letters O, B, A, F, G, K and M, with O being the hottest and M being the coolest). Each of these classes have special properties, relating to temperature and spectra. A common mnemonic for spectral classification is "Oh Be A Fine Girl, Kiss Me".

Type	Temperature (Kelvin)	Color	Hydrogen
O	30,000-60,000	Blue	Weak
B	10,000-30,000	Blue-White	Medium
A	7,500-10,000	White	Strong
F	6,000-7,500	White	Medium
G	5,000-6,000	Yellow	Weak
K	3,500-5,000	Yellow-Orange	Very Weak
M	2,000-3,500	Red	Very Weak

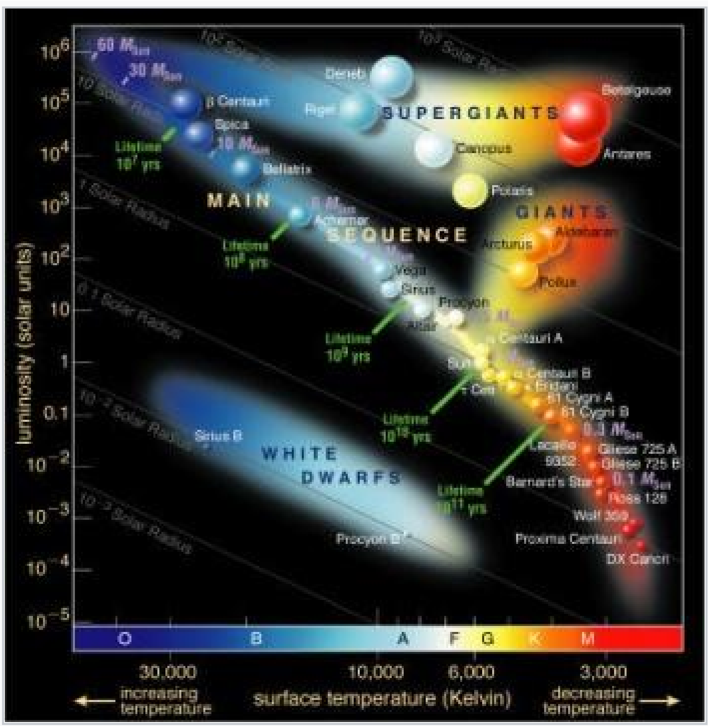
.

Yerkes Classification

Further, stars can be classified into different luminosity classes. This is done by the Yerkes Classification system:

Designation	Definition
0 or 1a	Hypergiant/Extremely Luminous Supergiant
1a	Luminous Supergiants
1ab	Intermediate luminous supergiants
1b	Less luminous supergiants

II	Bright giants
III	Giants
IV	Subgiants
V	Main Sequence
D	White dwarfs



The H–R Diagram

H–R Diagram

The **Hertzsprung–Russell** diagram relates the absolute magnitudes and luminosities of stars with their spectral types and temperatures. They are especially important in understanding stellar evolution. Although some diagrams may have more characteristics labeled on them than others, including characteristics not listed above like color index, they all have basically the same shape. Here, a basic introduction to the diagram and its usefulness will be given.

First, the H–R Diagram reveals key relationships in characteristics of stars. The first and most apparent of these is in the **main sequence**, which contains all of the stars that form a band in the middle of the diagram. The vast majority of stars fall within this band, including the Sun. Also, giants are found in a group above the main sequence, and white dwarves have their own conglomerate on the lower-left part of the diagram. The fact that these stars occupy distinct sections shows how a star's age can change its physical properties.

Another use of the H–R Diagram is that it can predict the location of a new, previously unknown star based on certain observations. For example, say a new star was discovered that had a temperature of 10,000 K and was known to be part of the main sequence. By looking at the diagram, it can be predicted that the star will have a luminosity of between 100 to 1000 solar luminosities.

The axes of H–R diagrams relate the luminosity of the star (often in relation to the Sun), to the temperature of the star. Temperatures can be represented in kelvins, through Spectral Class (Letters O, B, A, F, G, K and M), or both.

Variable Stars

Variable stars are split into two categories, intrinsic variables and extrinsic variables.

Intrinsic Variable Stars

These variables vary in brightness due to changes in the properties of the star itself. For example, pulsating variable stars expand and contract, increasing their radius and changing their luminosity. The most well known type of variables stars are:

- **Cepheid Variables** are stars that lie on the instability strip and have a fixed period-luminosity relationship. This relationship allows for the determining of distances to objects and galaxies. Additionally, Cepheid variables pulsate via the kappa-mechanism, where if the opacity of a star increases with temperature, more heat is trapped, causing the star to expand. However, as it expands, it becomes more transparent, releasing that heat, and decreasing in size once again.
- **RR Lyrae Variables** are stars that are similar to Cepheid variables, but are older and have shorter periods than Cepheids. They have relatively lower mass so are more common than Cepheids, but they are also fainter. The brightness varies based on similar mechanism as Cepheids, although they can have modulation in periods called the Blazhko effect due to resonance.
- **Mira Variables** are asymptotic giant branch red giants that have luminosity amplitudes of 2 to 11 magnitudes. The prototype of this type of star was Omicron Ceti, also known as Mira. The entirety of the star is expanding and contracting, causing the fluctuations in luminosity.

Extrinsic Variable Stars

Extrinsic variable stars change in luminosity as a result of external changes.

- **Rotating variable stars** vary in brightness due to its rotation, potentially causing sunspots to appear into view. These darker regions on the star reduce the luminosity, and thus appear to have variable luminosity.
- **Eclipsing variable stars** are stars that vary in brightness due to our view being obscured by another object. Just as astronomers can detect the minute difference in brightness of exoplanet transits in transit photometry, they can detect the variations in brightness when a star is eclipsed

by other objects--typically a companion star. As the secondary star travels around the primary, the primary star's brightness appears to dim, even though the star itself may not be undergoing any changes to its properties.

Groups of Stars

Astronomy also frequently deals with groups of stars, in addition to stellar properties themselves.

Stellar Populations

Populations of stars are classified by their metallicity, or by how much heavy metals a star has.

- **Population I** has the greatest concentration of metals, and most of them are relatively new stars that have taken metals expelled from other stars. The Sun is included within this group, as are many stars in the outer reaches of our galaxy. These make up the majority of stars in spiral and irregular galaxies. Open clusters, which are mostly located in the spiral arms of a galaxy contain mostly Population I stars.
- **Population II** has some heavy metals, but not as much as Population I, as they are older and did not benefit from as much metal dust as newer stars did. Stars in globular clusters and near the core of our galaxy belong to this population. Smaller galaxies also have more stars in this population. Population II stars also make up the majority of stars in elliptical galaxies. There is also a hypothetical
- *Population III* consists of the very first stars with little to no metal content, as they did not exist near the beginning of the universe. They did not last very long, but helped the metals to form for the later populations.

Math and Calculations

A notorious portion of the Astronomy event is the math portion. Due to the abstract nature of some of the concepts in the event, and the fact that these concepts are unlikely to be covered in any depth in any high school class, the math portion can be very intimidating to some. However, at its core, the math is not that difficult, and the difficulty is knowing how to apply these mathematical relationships, as opposed to actually using them to crunch the numbers. Developing a greater grasp on the math and becoming able to perform calculations accurately can help an Astronomy team go from being decent at the event to becoming very good at the event. Being comfortable with these equations can also help develop a deeper understanding of the governing relationships.

For the competition itself, math questions may vary. Some will be simple plug-and-play questions, whereas others will require more critical thinking, either by using multiple equations to arrive at the answer, using provided data to determine a relationship, or other various tasks. Either way, practice is very important with the Astronomy math. Luckily, the math does not normally change from year to year in the same way that the DSOs or the overall governing topic do, so past tests are a great resource for studying these. This is especially important because, on most tests, math is graded as partial credit. This means that even if the wrong answer is given, work that demonstrates an understanding of the concept can still earn points.

Units

Below are some of the most useful units encountered in Astronomy.

Arcminutes and arcseconds: An arcminute (symbol) is 1/60th of a degree, and an arcsecond (symbol) is 1/60th of an arcminute. Astronomy involves a lot of angles on the sky, and they are tiny, so arcseconds are commonly used. For example, the Moon appears about 1800 arcseconds across.

- Astronomical units: 1 astronomical unit (symbol au or AU) is (approximately) the average distance between the Earth and Sun.
- Parsecs: An object that is 1 parsec (1 pc) away from Earth and 1 astronomical unit wide will appear to be 1 arcsecond wide on the sky ("subtends" 1 arcsecond); equivalently, an object 1 parsec away from Earth has a parallax angle of 1 arcsecond (discussed in the Parallax section below). However, the parsec is used widely throughout astronomy in contexts other than parallax. On large scales, 1 kiloparsec (kpc) is one thousand pc, and 1 megaparsec (Mpc) is one million pc.
- Light years: A light year (ly) is the distance light travels in one year; other units such as the light minute and light second are defined similarly.
- Solar units: The solar mass ($M_\odot$) is the mass of the Sun, and the solar radius ($R_\odot$) and solar luminosity ($L_\odot$) are defined similarly. The solar effective temperature ($T_\odot$) is the temperature of a blackbody (discussed in the Radiation Laws section) that emits the same amount of light as the Sun, and thus is essentially the temperature that the Sun "acts" like it has in terms of the light it emits. The actual temperature of the Sun depends on the distance from the core.
- Angstrom: One angstrom (Å) is a tenth of a nanometer, or equivalently 10−10 meters. It is sometimes used to measure wavelengths.

Orbital Motion

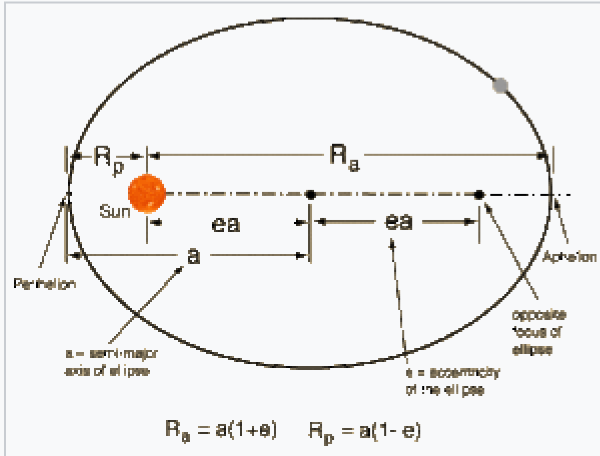
A significant part of the math involved in Astronomy relates to orbital motion, either between a planet and a star, or between stars in a binary system.

Kepler's Laws

Kepler's Laws govern the orbits of satellites. They were originally formed with respect to planetary motion around the sun, but they apply to other elliptical orbits as well.

Kepler's First Law

The first law says that **all of the orbits of the planets are elliptical with the Sun at one focus.** In terms of ellipses, the foci are two points along the *semi-major axis* (a in the diagram) of the ellipse around which the planet orbits. At any given point in time, the sum of the planet's distances to both foci is constant, giving it is slightly flattened shape. In the case of a circle, both foci are at the same point. The diagram below illustrates this point.



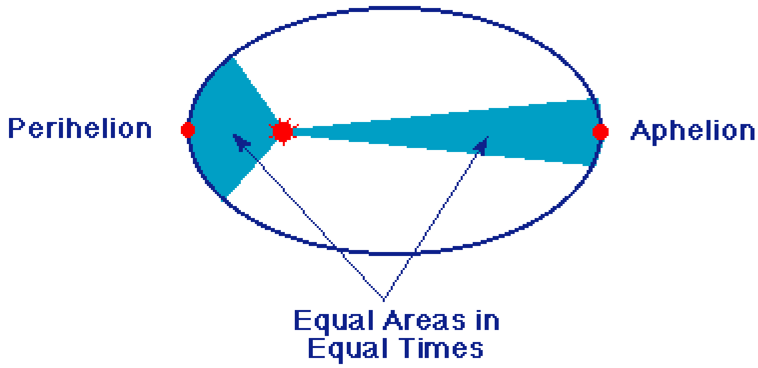
A diagram demonstrating Kepler's First Law. For a more basic diagram, see the Solar System page.

Elliptical orbits have a number of important properties.

- The **semi-major axis**, a, and **semi-minor axis**, b, determine the size of the ellipse. The semi-major axis is half the longest line segment across the ellipse, and the semi-minor axis is half the shortest line segment across the ellipse (perpendicular to the semi-major axis). For a circular orbit, the lengths of the semi-major and semi-minor axes are both the radius of the circle. Since the semi-minor axis can be computed from the semi-major axis and eccentricity, in astronomy it is more common to give the semi-major axis and eccentricity as parameters of the ellipse rather than the semi-major and semi-minor axes together.
- The **eccentricity**, e, of an ellipse is a unitless measure of how "squashed" the ellipse is. A circle has an eccentricity of 0, and as ellipses deviate more from a circle the eccentricity increases towards 1. In mathematical terms, the eccentricity is defined as the ratio e=ca, where c is the distance from either of the foci to the center of the ellipse, and a is the semi-major axis.
- The **periapsis** (also called the perihelion for orbits around the Sun or perigee for orbits around the Earth) of an orbit is the point at which the satellite is closest to the central object it is orbiting. The periapsis distance is given by the formula Rp=a(1−e). A common mistake is to think that the periapsis distance is the same as the semi-minor axis, since at the semi-minor axis the object is closest to the center of the ellipse. However, the Sun is *not* at the center of the ellipse--as stated above, it is at one of the foci instead.
- The **apoapsis** (also called the aphelion [orbiting the Sun] or apogee [orbiting the Earth]) is the point at which the satellite is farthest from the central object it is orbiting. The apoapsis distance is given by the formula Ra=a(1+e).

Kepler's Second Law

The second law is slightly more complex. This law says that **a planet traces out equal areas in equal time**. Since the satellite does not trace out as much area when it is closer to the Sun, it has to move faster in order for this law to be true, so this law proves that objects move faster the closer they are to the central object. This law is more easily explained with a diagram.



Proving this law requires a little bit of physics and calculus. This YouTube video has a very clear and direct explanation of this, which is understandable even without a background in calculus. A quick summary of the video is that an elliptical orbit can be regarded as a circular orbit when the angle that the object is tracing out is infinitely small, so by manipulating the formulas for angular momentum ($L=mv\perp r$) and partial area of a circle ($A=\theta r22$), a value for the change in area with respect to the change in time (dAdt for those familiar with derivatives) can be found. This expression only depends on the angular momentum (which is always conserved) and the mass of the satellite, neither of which changes over time. Therefore, Kepler's Second Law must be true.

Kepler's Third Law

All of these laws are important for a basic knowledge of astrophysics, but Kepler's Third Law is the one of most relevance to the Astronomy event. According to this law, **the square of the satellite's period is directly proportional to the cube of the length of its semi-major axis.** This law can be presented symbolically as

$p2\propto a3$. If we want an actual equation, we have to use a constant.

$$p2=(4\pi 2GM)a3$$

Where G is the gravitational constant ($6.67\times 10-11N\cdot m2/kg2$) and M is the total mass of the system (which can often be approximated as the mass of the central object when it's much larger than its satellite, but not when the objects are of similar mass, like in a binary star system). When applying the above formula, you should typically use SI units: in other words, p is in seconds, M in kilograms, and a in meters.

We can use the case of Earth's orbit to simplify this formula. When p is expressed in solar years, M is expressed in solar masses, and a is expressed in AU, the factor of

$4\pi 2/G$

cancels out. Then, the formula is simply

$$p2=a3M$$

Where M is the total mass of the system in solar masses. Thus, when talking about our solar system, the mass is 1 solar mass and we get the most common form of Kepler's Third Law:

$$p2=a3$$

IMPORTANT: This formula only works if the correct units are used such that everything cancels. If years are not used for period or AU is not used for semi-major axis length, then it will likely result in an incorrect answer.

Binary Systems

Orbital calculations involving planets often assume that the location of the massive body (e.g. the sun) is fixed and that the less massive object orbits the center of mass of the massive body. This approximation works for most practical purposes when the ratio of the bodies' masses is very large. However, more technically, both bodies in a binary system orbit their shared center of mass, or barycenter. For example, in a system that contained only Jupiter and the Sun, the barycenter would be located just outside the sun (it actually shifts around constantly with multiple significantly massive planets). The difference is far more pronounced when the bodies are similar in mass, such as Pluto and Charon or two binary stars.

For the remainder of this section, we will assume two massive bodies in isolation. The physics becomes far more complicated when one considers more than two bodies. One of the most important things to note is that the two bodies orbit in direct opposition to each other with the same period. The more massive body is always closer to the center of mass, while the less massive object orbits further from the barycenter. These are related such that for an object with a mass, ma, and a distance from the barycenter, ra, and a second object with a mass, mb, and a distance, rb:

$$mamb=rbra$$

As the period is constant, the object must travel the full circumference (for a circular orbit) in one period. Therefore as circumference is proportional to radius, so also the orbital velocity is directly proportional to the distance from the barycenter.

$$vara=vbrb$$

We can also extend Kepler's Third Law to binary systems. Using the result above that:

$$p2=a3M$$

where M is the mass of the system, we substitute the sum of the values of both stars, yielding:

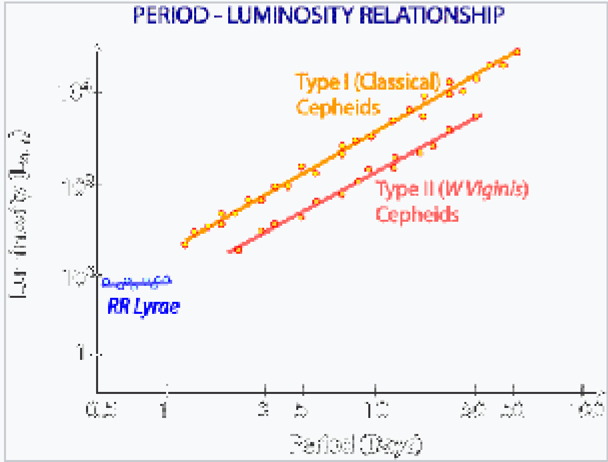
$$MA+MB=a3p2$$

Here, MA,MB are the masses of the stars, both in solar masses, a is in AU, and p is in years. This only works because again, the units cancel out.

Determining Distances

A large part of the Astronomy event is being able to determine distances to objects in space from Earth. Often a question will give certain information and the participant will have to interpret and use the information to find the distance, luminosity, or some other characteristics of the object in question.

Cepheids and RR Lyrae



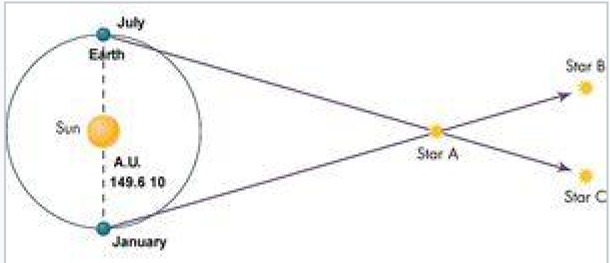
A period-luminosity graph

Cepheids and RR Lyrae are two types of variable stars that are especially good for finding distances to galaxies or other groups of stars because they have direct correlations between luminosity and period. In both Cepheids and RR Lyrae, the longer the period, the higher the luminosity. Cepheids typically have periods of about 1 to 50 days. **Type I Cepheids**, or Classical Cepheids, are brighter, newer Population I stars (see section about stellar populations above for an explanation). **Type II Cepheids** are similar to Type I in terms of the relationship, but they are smaller, dimmer Population II stars. These are also called *W Virginis* stars.

RR Lyrae are different from Cepheids in that they are older and fainter than Cepheids. RR Lyrae stars typically have shorter periods than Cepheids - usually less than one day. They have masses about half that of our Sun, and are Population II stars. Also, the luminosity does not increase as much to a change in period, as **most RR Lyrae have absolute magnitudes close to 0.75**. Therefore, they are only useful in our galaxy and the one closest to us, Andromeda. However, this makes them very useful in determining distance, because once an RR Lyrae star has been found, one only needs to know the apparent magnitude in order to put it into the distance modulus equation and find distance. RR Lyrae have been linked to globular clusters, since most variable stars in globular clusters are RR Lyrae. They are named after the original RR Lyrae in the constellation Lyra.

These variable stars are useful in calculations because once the period is found, the luminosity can be calculated or determined through the use of a period-luminosity graph. Then, through other formulas, the distance can also be determined. This gives them the use as "standard candles" in galaxies relatively close to ours in our universe. NGC 4603, a past DSO, is the farthest galaxy that a Cepheid has been used to calculate distance at 108 million light years away. Cepheids are more rare due to their shorter life span, being more massive than RR Lyrae. Their brightness makes it easier to observe, and they are especially useful if there is a Supernova Ia in the same galaxy, to serve as a calibration to the distance ladder.

Distance Equations



A diagram of parallax showing how the apparent position of Star A changes from January to July. Over this time span, the Earth travels 2 AU, so half of the total change is used as the value for parallax, in arcseconds. This value can then be used to determine distance in parsecs using 1/parallax.

Triangulation/Parallax

Triangulation is often used to determine distances. This method is based on parallax shifts, apparent changes in a star's location when viewed from different locations. The *parallax* of a star is one-half of the angular shift seen of an object produced over six months, which corresponds to a distance of 2 AU. In other words, it is the angle subtended by a star as the Earth moves by 1 AU. The parallax decreases as distance increases. The equation for parallax is:

$$D=1p$$

where p is measured in arcseconds, and D is measured in parsecs. (In fact, this is how a parsec is defined--the distance to a star that has a parallax of one arcsecond). Parallax is only useful to measure stars up to 1000 parsecs away, since past that the parallax is so small that it is not accurate.

Hubble's Law

Hubble's Law uses the fact that the universe is expanding to determine distance. Due to the universe's expansion, objects that are far away, such as other galaxies or galaxy clusters, are moving away from us. Edwin Hubble found that the recessional velocity is proportional to the distance away an object is and created an equation, v=HoD, where v is the recessional (or "radial") velocity, Ho is Hubble's constant, and D is the distance. The exact value of Hubble's constant is disputed, but most values are about 70 km s^{-1} Mpc^{-1}.

Hubble's Law can only be applied to objects that are moving away from the Milky Way due to the universe's expansion. For instance, we can't use Hubble's Law for another star in our galaxy.

The value of v is found by looking at an object's spectrum. The recessional velocity is approximately the redshift multiplied by the speed of light (for high/relativistic redshifts, this does not hold), and in order to find redshift, a spectrum must be used. Redshift is how much a spectrum shifts toward the red side of the spectrum (i.e. an increase in wavelength) due to recession. Redshift, or Z, is found by dividing the change in wavelength of the spectrum by the wavelength the object was expected to have (i.e. it is the percent change in wavelength, expressed as a decimal).

Distance Modulus

The distance modulus equation is also very important. It relates an object's distance with the difference between the apparent magnitude (m) with the absolute magnitude (M). This difference is known as the *distance modulus*.

$$5\left(\log_{10}(d)-1\right)=m-M$$

where d is in parsecs, and m,M are apparent and absolute magnitudes respectively.

$\log_{10}$ is the standard base-10 logarithm (the "log" button on most calculators).

This equation can be written in many different ways so that different values can be found (for instance, rearranged for the distance, it is $d=10^{(m-M+5)/5}$), but the essential purpose of the formula remains the same. A good way to practice using this equation before the competition is to take the apparent magnitude and approximate distance to a DSO and use them to find the absolute magnitude. This experience will save time if this concept comes up during a test.

Radiation Laws

The radiation laws show relationships between stellar temperature, radius, and luminosity. Both Wien's Law and Stefan's Law are proportionality statements that can be turned into equations by introducing a proportionality constant. In this event, math questions will typically approximate a star or other luminous object with a black body.

Wien's Law: Wien's displacement law states that the wavelength where a blackbody's radiation curve peaks is inversely proportional to the temperature. In equations,

$$\lambda_{max} \propto \frac{1}{T}, \lambda_{max}=\frac{b}{T}$$

,

where λ_{max} is the wavelength at which the output of radiation from an object (in technical terms, the spectral radiance) is at a maximum, T is temperature in kelvins, and $b=2900 \mu m \cdot K$ is known as Wien's displacement constant. The units of b you choose should align which the units of wavelength used: for instance, if wavelength is in meters, you should use $b=2.9\times10^{-3} m \cdot K$, and if wavelength is in nanometers, you should use $b=2.9\times10^{6} nm \cdot K$.

For example, the sun has surface temperature $T=5778K$, so its radiation peaks at $\lambda_{max}=\frac{2.9\cdot10^{-3} m\cdot K}{5778K}=502nm$, a yellow-green color.

Stefan–Boltzmann Law: The Stefan–Boltzmann law states that the total energy emitted from a black-body per unit surface area is proportional to the fourth power of its temperature. In equations,

$$j^* \propto T^4, j^*=\sigma T^4,$$

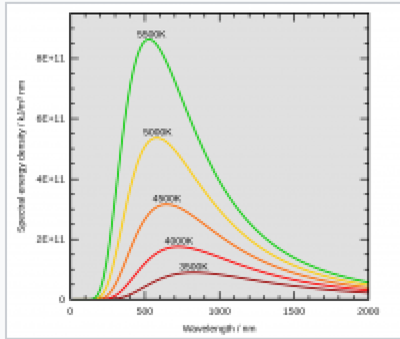
where j^* is the total energy emitted per unit area (in other words, the total radiated flux across all wavelengths), T is temperature in kelvins, and $\sigma=5.67\cdot10^{-8} \frac{W}{m^2 \cdot K^4}$ is known as the Stefan–Boltzmann constant.

Most blackbodies we encounter are spheres, which have surface area $A=4\pi R^2$, where R is the radius of the object. Combining these equations, the total luminosity is

$$L=4\pi R^2 \sigma T^4.$$

For example, the sun has radius and temperature $R=6.96\cdot10^{8}m$, $T=5778$ K. Plugging these into the equation, its luminosity is $3.85\cdot10^{26}W$, which is close to the experimental value of $3.83\cdot10^{26}W$.

Planck's Law: Planck's law states that a hotter blackbody emits more energy at every frequency than a cooler blackbody. The equation form of the law is complicated, but on a radiance vs. temperature graph the curve for a hotter blackbody never dips below that of a cooler one.



The actual equation for Planck's law, known as the Planck function, is rarely used in calculation - it is usually only used in questions conceptually. It is a multivariable function that describes the radiance of a blackbody at different temperatures and wavelengths (or frequencies) of light.

Inverse Square Law

An inverse square law is a relationship in which a quantity is inversely proportional to the square of the distance relating to that quantity. For example, suppose one measures intensity I_1 at distance D from the source. By the inverse square law, we have:

$$I_1 \propto \frac{1}{D^2}$$

.

This law also applies to Newton's Law of Gravitation. The law states that:

$$F=\frac{GMm}{r^2}$$

where r is the distance between the two objects. By the law, $F \propto \frac{1}{r^2}$.

The law is very common in physics - it also applies to the electrostatic force and the intensity of sound wave in a gas.