

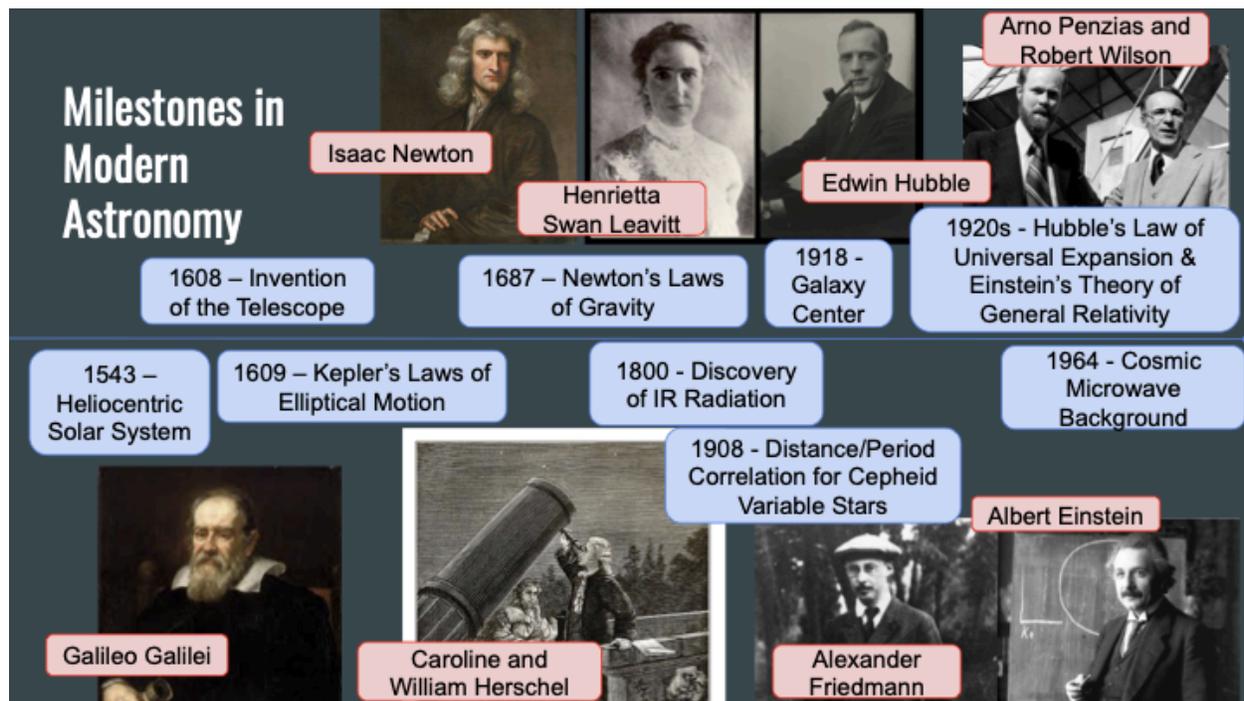
# Lecture 1: Overview and the Night Sky at a Glance

## Early Origins of Astronomy

Most ancient civilizations started with myths, legends, religions based around astronomical phenomena, like the **Bushmen** in South Africa, **Mayans** in Central America

But they built on this to develop **theories**, **models**, and **instruments** to study and explain motions of stars and planets, and spread their knowledge throughout Europe, Africa, Asia, and the Americas

While heliocentrism and invention of the telescope are seen as the start of modern astronomy (i.e. as a “science”), there were thousands of years of detailed computationally-driven and phenomenological astronomy preceding it from all over the world.



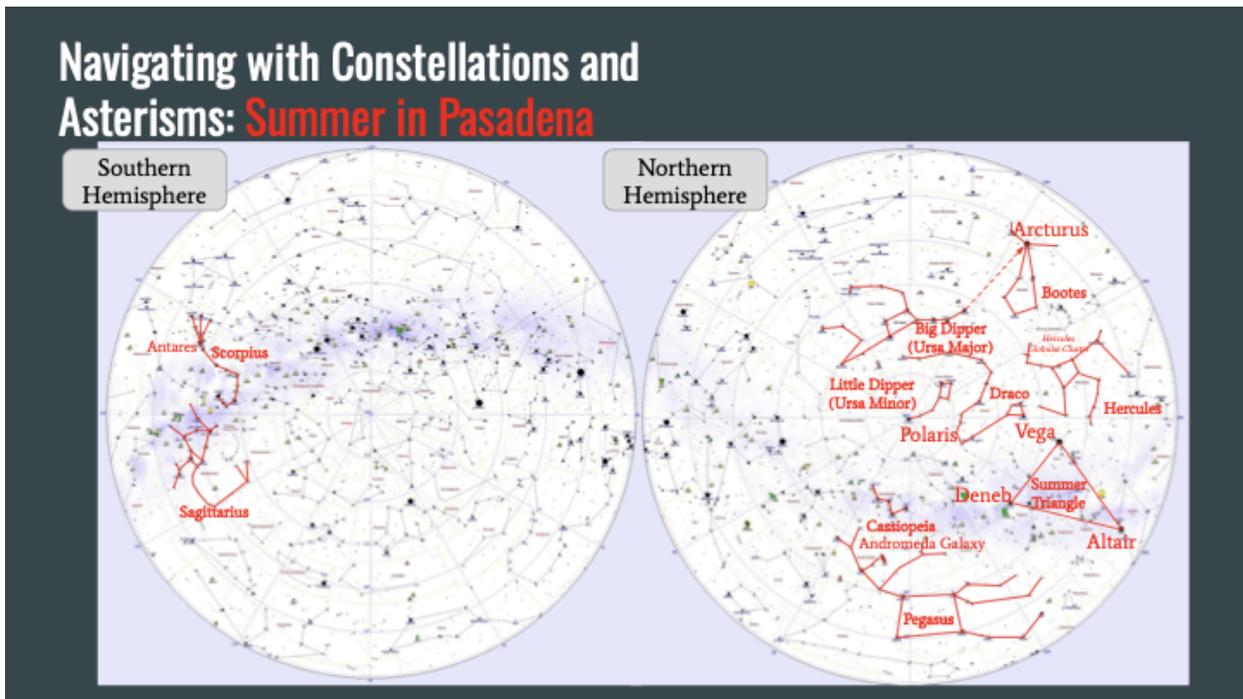
## Navigating the Night Sky

### Distance scales:

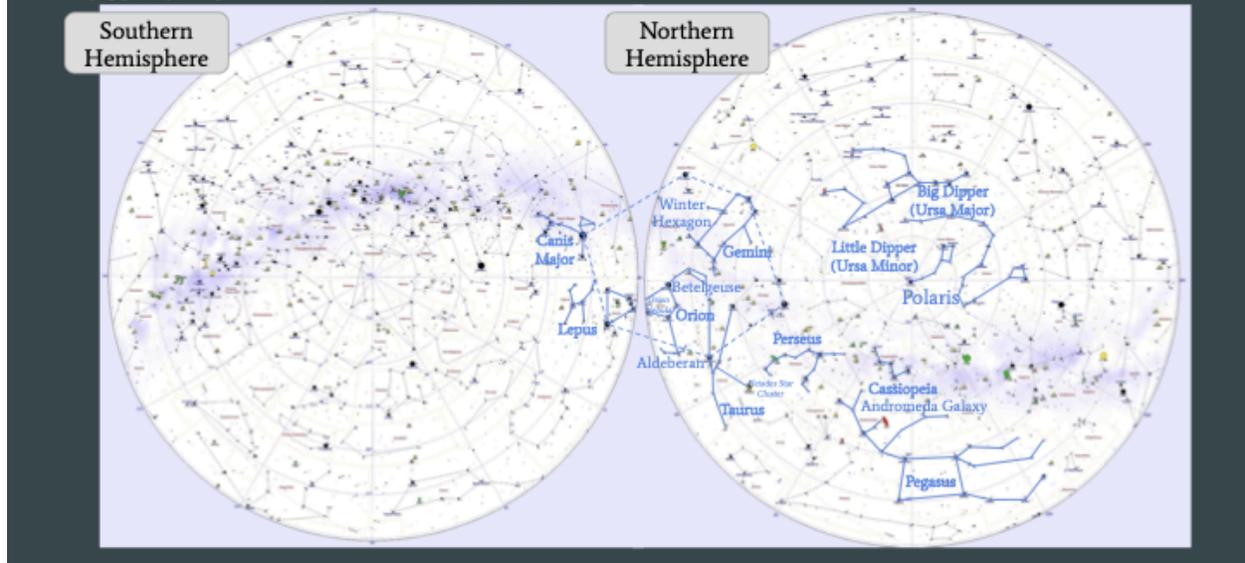
- **Astronomical unit** - distance from **Earth** to **the Sun**
  - 1AU = **93 million** miles

- **Parsec** - a measurement of distance based on apparent position of stars due to Earth's orbit
  - 1 parsec (pc) = 200 thousand AU
  - Distance from the Sun to Galactic Center is 8 kpc
- **Light year** - distance travelled by light in a year
  - **Speed of light:**  $c =$  300 million meters/second = 670 million mph
  - 1 light year (ly) = 0.3 parsecs

We can orient ourselves in the night sky with **constellations** and **asterisms**:



## Navigating with Constellations and Asterisms: Winter in Pasadena



- **Celestial Coordinates** - coordinate system centered on Earth and aligned with Earth's longitude/latitude system
  - **Right Ascension** – celestial 'longitude'
  - **Declination** – celestial 'latitude'
  - It takes 1 **Sidereal** Day (23 hours and 56 minutes) for the same RA to be overhead, and explains why the stars appear to 'shift' by 4 minutes each Earth day (24 hours)

## Star Formation and Evolution

**The Interstellar Medium** - gas and dust between the stars in the galaxy

- The ISM is composed of...
  - ~70% **Hydrogen**: element with **1 proton** and **1 electron** ( $Z=\text{nuclear charge number}=1, A=\text{atomic number}=1$ )
  - ~28% **Helium**: element with **2 protons**, **2 neutrons**, and **2 electrons** ( $Z=2, A=4$ )
  - ~1.5% "**metals**": any element heavier than Helium (e.g. Lithium, Beryllium, Sodium, Iron) that are produced from stellar explosions
  - ~0.5% **dust**: silicates, carbon ( $Z=6$ ) molecules, hydro-carbons, graphite
    - **Extinction** - dimming of light from **scattering** and **absorption** by dust particles,  $A_\lambda$

- **Absolute magnitude** - intrinsic brightness  $M_\lambda$
- **Apparent magnitude** - observed brightness  $m_\lambda$
- $m_\lambda = M_\lambda + A_\lambda + 5 \log_{10} \left( \frac{d}{1 \text{ parsec}} \right) - 5$
- \*\*\*Brighter = negative magnitudes\*\*\*
- \*\*\*Fainter = positive magnitudes\*\*\*

**Star Formation** - Dust and gas clouds collapse under gravity to form stars

- **Energy** - capacity to move or change matter in some way; **energy is always**

**conserved:**  $E_{\text{initial}} = E_{\text{final}}$

- **Kinetic energy** - energy due to motion of an object:  $E_{\text{kinetic}} = \frac{1}{2}mv^2$

- **Thermal energy** - heat energy due to microscopic motions of particles:

$$E_{\text{thermal}} = \frac{3}{2}NkT$$

- **Potential energy** - stored energy

- **Gravitational potential energy** - capacity to move under the force of

**gravity:**  $E_{\text{grav}} = \frac{-GMm}{r} \approx mgr$  ( $g = -9.81 \text{ m/s}^2$  on Earth)

- An extended object with mass  $M$  and radius  $R$  has total gravitational

binding energy  $E_{\text{grav}} = \frac{-3}{5} \frac{GM^2}{R}$

- **Jeans Criteria** - a cloud of dust and gas will **collapse** under gravity if:

$$\text{■ } M > M_J = \sqrt{\frac{3}{4\pi} \left( \frac{10kT}{\rho_0 G \mu m} \right)^3} \text{ or } R < \sqrt{\frac{15kT}{4\pi G \rho_0 \mu m}}$$

## Stellar Structure

- Enclosed mass  $M(r)$  = mass within radius  $r$

- Density = mass per unit volume, e.g. for a uniform sphere,  $\rho = \frac{M}{\frac{4}{3}\pi R^3}$

- Equations of stellar structure:

- **[1] Hydrostatic equilibrium** - gravity and **pressure** (force exerted per unit area by moving particle) must be balanced:  $\frac{dP}{dr} = - \frac{GM(r)\rho(r)}{r^2}$

- **[2] Mass conservation** - mass cannot be created nor destroyed:  $\frac{dM}{dr} = 4\pi r^2 \rho(r)$

- **[3] Pressure Equation of State** - describes how a specific gas (or light) behaves

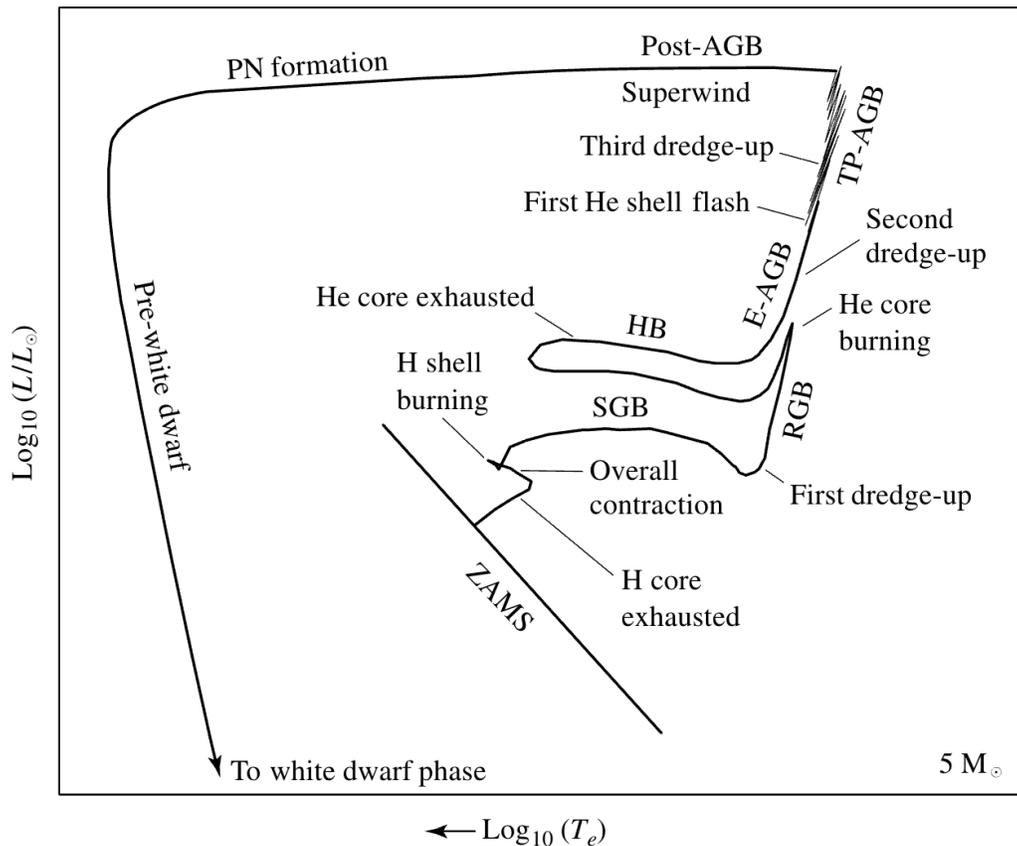
- *Ideal gas* follows  $PV = NkT$

- *Radiation* follows  $P = \frac{1}{3}aT^4$

- **[4] Luminosity (power radiated by the star) gradient** - describes how energy is radiated per unit time throughout the star:  $\frac{dL}{dr} = 4\pi r^2 \rho(r) \epsilon(r)$
- **[5] Radiative Transport** - describes how energy is transported throughout the star
  - **Radiation:** energy is transferred by light  $\frac{dT}{dr} = \frac{3}{4ac} \frac{\kappa \rho}{T^3} \frac{L}{4\pi r^2}$
  - **Adiabatic Convection:** energy is transferred by motion of gas 'clumps'  $\frac{dT}{dr} = \left(\frac{1}{\gamma} - 1\right) \frac{\mu m}{k} \frac{GM}{r^2}$

### Stellar Evolution

- **The Hertzsprung-Russell (HR) Diagram** - Shows the evolution of stars' **temperature** and **luminosity** throughout their life cycles, used to classify stars



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- **Main Sequence** - where stars spend most of their lifetimes fusing **Hydrogen** into **Helium** in their cores ( $T \sim 10^7$  K)
  - **1 Solar Mass ( $M_{\odot}$ )** =  $2 \times 10^{30}$  kg

- **Low Mass Stars ( $0.3 - 1.2 M_{\odot}$ )** use the **proton-proton chain** to fuse 6 Hydrogen atoms into 1 Helium atom:
- **High Mass Stars ( $>1.2 M_{\odot}$ )** use the **Carbon-Nitrogen-Oxygen (CNO) Cycle** to fuse 4 Hydrogen atoms into 1 Helium atom using C,N,O as intermediaries
- Stars maintain stability by a feedback process: fusion increases the mean molecular weight → decreases the outward pressure → causes gravity to contract the core → causes core to heat → causes pressure to increase → causes core to expand → causes temperature to decrease
- **Sub-Giant Branch** - after Hydrogen has been exhausted, the core needs to heat up to  $T \sim 10^8 \text{ K}$  in order to fuse **Helium**
  - Core contracts, heats, and releases **gravitational energy** as radiation
  - In the **shell**, Hydrogen continues to fuse into Helium which falls onto the core
  - Radiation from core heats up the envelope causing it to **expand** and get **brighter**
- **Red Giant** – convective mixing between the core and envelope
  - envelope is now **bigger, redder, and colder**, which is why they're called 'red giants'
- **Horizontal Branch** - once the core reaches  $T \sim 10^8 \text{ K}$  it fuses **Helium** into **Carbon and Oxygen** via the **triple alpha process**
- **Asymptotic Giant Branch** - after Helium has been exhausted, the core needs to heat up in order to fuse **Carbon** and **Oxygen**
  - This is the same process as the **Sub-Giant Branch**, but with heavier elements
- For stars  $< 4 M_{\odot}$ :
  - The core doesn't have enough mass to keep contracting and heating up, so it will never be able to fuse Carbon and Oxygen
  - Envelope will keep expanding until it **blows away**
  - **White Dwarf** - leftover core of Carbon and Oxygen
  - **Electron degeneracy pressure** - quantum mechanical pressure between electrons that supports White Dwarf stars against gravitational collapse
  - **Chandrasekhar Mass** - maximum mass of a White Dwarf before it collapses under gravity;  $M_{CH,WD} = 1.44 M_{\odot}$
- For stars between  $4 - 8 M_{\odot}$ :
  - Repeat the Asymptotic Branch again, but fuse **Carbon and Oxygen** into **Neon and Magnesium**

- The resulting core doesn't have enough mass to keep contracting and heating up, so it will never be able to fuse **Oxygen, Neon and Magnesium** and will also become a **White Dwarf**
- For stars  $> 8M_{\odot}$ :
  - Repeat the Asymptotic Branch multiple times until they fuse all lighter elements into an **Iron** core
  - The core can't fuse **Iron** without losing energy; instead it breaks it down into **neutrons** when it reaches  $T \sim 10^{10} K$
  - **Neutron degeneracy pressure** - quantum mechanical pressure between neutrons that supports White Dwarf stars against gravitational collapse
  - Outer layers will **collapse** under gravity, and "bounce" off the core, exploding as a **core-collapse supernova**
  - **Neutron star** - leftover core of neutrons
  - **Chandrasekhar Mass** - maximum mass of a Neutron Star before it collapses under gravity into a **Black Hole**;  $M_{CH,NS} = 1.4M_{\odot}$

## Orbits and Binary Stars

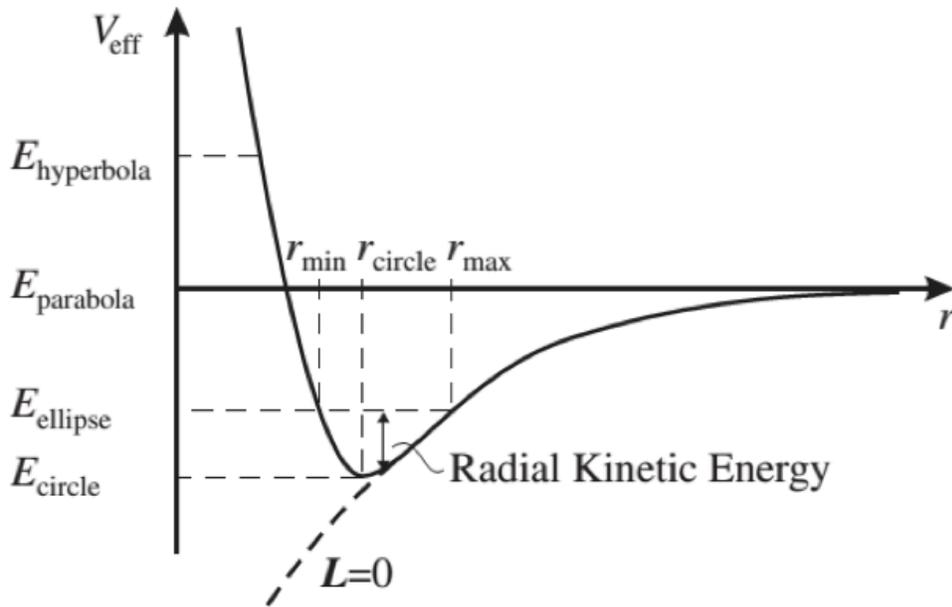
Most high mass stars are in **orbit** with other stars:

	Single	Binary	Triple+
Sun-like stars	<b>60%</b>	30%	<b>10%</b>
O-type stars	6%	<b>21%</b>	73%

The total energy for two stars in orbit:

$$E_{total} = E_{kinetic} + E_{grav} = K_{eff} + \frac{V_{eff}}{\mu} = \frac{1}{2}\mu(\dot{r})^2 + \mu\omega^2 r^2 - \frac{1}{2}\mu\omega^2 r^2 - \frac{GM_1M_2}{r}$$

If the total energy is  $<0$ , the orbit is **bound**; if the total energy is  $>0$  the orbit is **unbound**



### Kepler's Laws of Elliptical Orbits

1. Stars in Planets in bound systems move in **elliptical orbits** around the **center of mass**
2. The area swept out by a radius vector per unit time is **constant**
3. The orbital **period** squared is proportional to the **semimajor axis** cubed:

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

**Equipotential Surfaces** are 3D surfaces where the effective potential is constant

- When a star expands and overflows its **Roche Lobe**, it can start to transfer mass to the companion by **accretion**

Types of Binaries:

- **Cataclysmic Variable (CV)** - white dwarf star accreting from an M-dwarf star; eventually the white dwarf will collapse under the new mass and explode as a **Type 1a supernova**
- **X-ray Binaries** - neutron star or black hole accreting from a sun-like star
- **Millisecond Pulsar** - after accreting, a neutron star can spin up to fast rotation rates