NOTES:

- absolute magnitude – a measure of how bright a star would be if it were seen from a standard distance (32.6 LY away)
- apparent magnitude – the brightness of a star as seen from Earth
- For identical stars, L (luminosity) is intrinsic, so the ratio La to Lb is 1
- Calcium is not a common absorption line in the suns solar spectrum
- **Lower absolute value means it’s brighter**
    - Random: More negative absolute magnitude is brighter (take absolute value to find out which one’s brighter)
    - White dwarves, protostars, and neutrons stars increase in density as more mass is added
    - A star with a positive absolute magnitude is NOT intrinsically brighter than a star with a negative absolute magnitude
- Planetary system formation theory
    - Planets must orbit in a flat plane
    - Planets DON’T orbit in one direction while close to the central star, and the opposite when farther away
    - Large planets have cleared orbital regions
    - Planets orbit in the same direction about the central star
    - Molecular cloud builds up due to strong gravity → part of the cloud collapses to form a star → another portion o f the cloud clumps together to form planets
- Drake equation answers the question “Are we alone in the universe” → estimates the number of communicative civilizations in the Milky Way

$$N = R_* \cdot f_P \cdot n_e \cdot f_l \cdot f_i \cdot f_c \cdot L$$

N = number of civilizations with which humans could communicate
R_* = mean rate of star formation
f_P = fraction of stars that have planets
n_e = mean number of planets that could support life per star with planets
f_l = fraction of life-supporting planets that develop life
f_i = fraction of planets with life where life develops intelligence
f_c = fraction of intelligent civilizations that develop communication
L = mean length of time that civilizations can communicate

- Thermal equilibrium
    - Temperature is constant; loss in energy through radiation = gain in energy through fusion
- Nebular theory of solar system formation
    - formed from the gravitational collapse of a giant interstellar gas cloud—the solar nebula. – (Nebula is the Latin word for cloud.)
    - Kant and Laplace proposed the nebular hypothesis over two centuries ago.

        - Cloud condenses and begins to spin and flattened into a protoplanetary disk and then became our solar system
        - Star heats up until fusion occurs
        - Theory supported by our system's orbital plane, direction, and rotation
        - Pluto's orbit and Venus do not support this theory
- Unless it's quickly combined with more nuclei, Helium-helium fusion creates Beryllium-8, a highly unstable isotope
- Algol paradox refers to the apparent inconsistency in the brightness variation of an eclipsing binary system
        - The Algol paradox refers to the observation that the binary star system, Algol, does not follow accepted models of stellar evolution. Typically larger mass stars will fuse through their hydrogen faster than lower mass stars. When a star runs out of hydrogen, it will move on to the giant stage, one of the later stages of evolution.
        - In the case of Algol, the lower mass star was observed to be a red giant, while the larger mass star was still on the main sequence. This seemed to defy our models of stellar evolution, but the problem was resolved when astronomers realized that mass could be transferred from one star to the other.
- The fictitious "angle" which varies linearly with time and defines the position of an orbiting body at a specific time is called the mean anomaly
- "Apsidal precession" refers to gradual change in the longitude of ascending node
- Quantum tunneling is NOT cause of perturbations in an elliptical orbit
        - Gravity of other planets, electromagnetic forces, atmospheric drag, radiation pressure, and relativistic effects are all causes of perturbations in an elliptical orbit
- The vernal equinox represents the origin for ecliptic longitude in the sky and occurs when the sun is on the ascending node of the celestial equator
- Sirius B is a white dwarf and an unseen binary companion to the brightest star in the night sky (Sirius A)
- Neutronium is the densest state of matter
- A star cluster is a useful natural "laboratory" for studying stellar evolution because the stars in a cluster all Have similar spectral type
- Kuiper belt = Donut-shaped disc in the outer Solar System, extending from the orbit of Neptune at 30-50 AU from the Sun
- Asteroids with low albedos are most easily observed with infrared light
- Cosmological constant measures the energy density of the vacuum of space → simplest explanation for dark matter

$$\underbrace{G_{\mu\nu}}_{\text{Law of an expanding universe}} = \underbrace{8\pi G T_{\mu\nu}}_{\text{All matter and energy in the universe}} \quad \text{Einstein's original equation}$$

$$\underbrace{G_{\mu\nu}}_{\text{Law of an expanding universe}} + \underbrace{\Lambda g_{\mu\nu}}_{\text{Cosmological constant}} = \underbrace{8\pi G T_{\mu\nu}}_{\text{All matter and energy in the universe}}$$

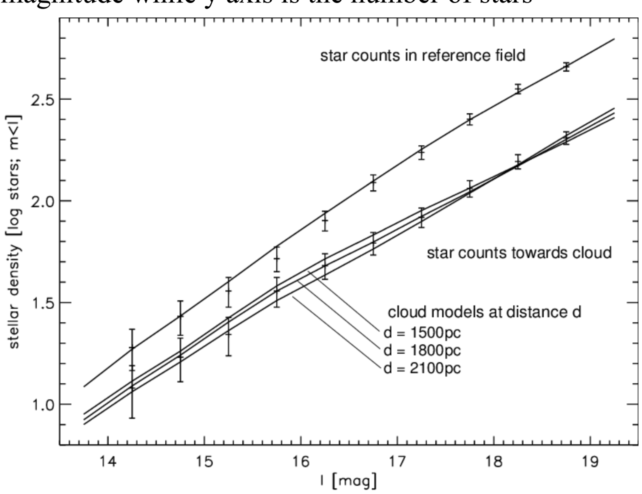
$$\underbrace{G_{\mu\nu}}_{\text{Law of an expanding universe}} = 8\pi G(\underbrace{T_{\mu\nu}}_{\text{All matter and energy in the universe}} - \bar{\rho}_{DE} g_{\mu\nu})$$

- Detection of sound waves in early universe → What we observe is not the sound waves themselves but rather the spectrum of light emitted from the compressions and rarefactions of the sound waves

- Jupiter and Saturn radiate more energy than they receive from the sun, most likely due to Gravitational contraction
- The orbits of comets are highly elliptical, and their semi-major axes are large so Most comets do not reappear in our sky very often
- Reflection nebulae are due to Scattered radiation from dust and are usually blue
- Lower stellar magnitude number (or apparent magnitude) is a brighter star
- Cosmic Microwave Background is best studied using radio wavelengths
- Metallicity measures the abundance of elements other than hydrogen and helium in an object
- In a system in which the planet exhibits an unexpectedly rapid precession of its orbit, what might be an explanation based on Keplerian mechanics → The presence of a massive object in the outer orbit
- Lyman-alpha lines in astronomical observation is a significant emission line of neutral hydrogen
- Cosmological principle = states that the universe looks the same from any location (on the large scale)
- Hawking radiation is a theoretical prediction for black holes. This phenomenon suggests that black holes Emit radiation due to quantum effects near the event horizon
- Blue loop = the stage in the life of an evolved star where it changes from a cool star to a hotter one before cooling again → makes a loop towards blue on the HR diagram

Absorption nebula (aka dark nebula):

- Extinction of an absorption nebula is commonly studied using a Wolf diagram. The x axis is the magnitude while y axis is the number of stars



- At lower magnitudes, the number of stars in the nebula and comparison group both increase together. After the limiting magnitude, the number of stars falls below the comparison group.
- A dark nebula or absorption nebula is a type of interstellar cloud, particularly molecular clouds, that is so dense that it obscures the visible wavelengths of light from objects behind it, such as background stars and emission or reflection nebulae.
- The extinction of the light is caused by interstellar dust grains in the coldest, densest parts of molecular clouds.
- Clusters and large complexes of dark nebulae are associated with Giant Molecular Clouds.

- Isolated small dark nebulae are called Bok globules. Like other interstellar dust or material, the things it obscures are visible only using radio waves in radio astronomy or infrared in infrared astronomy.
- Dark clouds appear so because of sub-micrometre-sized dust particles, coated with frozen carbon monoxide and nitrogen, which effectively block the passage of light at visible wavelengths. Also present are molecular hydrogen, atomic helium, $C^{18}O$ (CO with oxygen as the 18O isotope), CS, NH3 (ammonia), H2CO (formaldehyde), c-C3H2 (cyclopropenylidene) and a molecular ion N2H+ (diazenylium), all of which are relatively transparent. These clouds are the spawning grounds of stars and planets, and understanding their development is essential to understanding star formation.
- The form of such dark clouds is very irregular: they have no clearly defined outer boundaries and sometimes take on convoluted serpentine shapes. The closest and largest dark nebulae are visible to the naked eye, since they are the least obscured by stars in between Earth and the nebula, and because they have the largest angular size, appearing as dark patches against the brighter background of the Milky Way like the Coalsack Nebula and the Great Rift. These naked-eye objects are sometimes known as dark cloud constellations and take on a variety of names.

Molecular Clouds

A **molecular cloud**, sometimes called a **stellar nursery** (if star formation is occurring within), is a type of interstellar cloud, the density and size of which permit absorption nebulae, the formation of molecules (most commonly molecular hydrogen, H_2), and the formation of H II regions. This is in contrast to other areas of the interstellar medium that contain predominantly ionized gas.

Molecular hydrogen is difficult to detect by infrared and radio observations, so the molecule most often used to determine the presence of H_2 is carbon monoxide (CO). The ratio between CO luminosity and H_2 mass is thought to be constant, although there are reasons to doubt this assumption in observations of some other galaxies.[1]

Within molecular clouds are regions with higher density, where much dust and many gas cores reside, called clumps. These clumps are the beginning of star formation if gravitational forces are sufficient to cause the dust and gas to collapse.[2]

- **Gravitational collapse is the primary mechanism driving the process of star formation in molecular clouds**

Within the Milky Way, molecular gas clouds account for less than one percent of the volume of the interstellar medium (ISM), yet it is also the densest part of it. The bulk of the molecular gas is contained in a ring between 3.5 and 7.5 kiloparsecs (11,000 and 24,000 light-years) from the center of the Milky Way (the Sun is about 8.5 kiloparsecs from the center).[6] Large scale CO maps of the galaxy show that the position of this gas correlates with the spiral arms of the galaxy.[7] That molecular gas occurs predominantly in the spiral arms suggests that molecular clouds must form and dissociate on a timescale shorter than 10 million years—the time it takes for material to pass through the arm region.[8]

Perpendicularly to the plane of the galaxy, the molecular gas inhabits the narrow midplane of the galactic disc with a characteristic scale height, *Z*, of approximately 50 to 75 parsecs, much thinner than the warm atomic (*Z* from 130 to 400 parsecs) and warm ionized (*Z* around 1000 parsecs) gaseous components of the ISM.[10] The exceptions to the ionized-gas distribution are H II regions, which are bubbles of hot ionized gas created in molecular clouds by the intense radiation given off by young massive stars; and as such they have approximately the same vertical distribution as the molecular gas.

This distribution of molecular gas is averaged out over large distances; however, the small scale distribution of the gas is highly irregular, with most of it concentrated in discrete clouds and cloud complexes

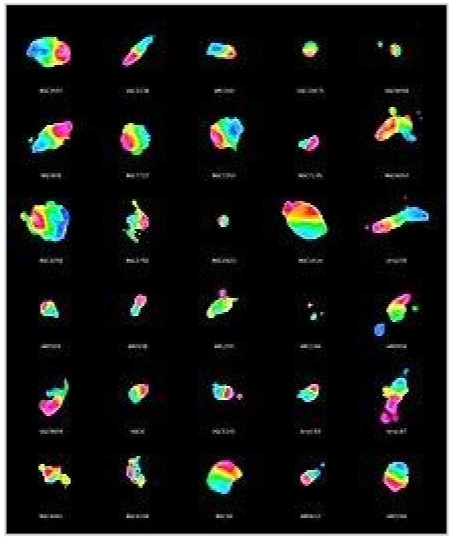
GIANT MOLECULAR CLOUDS:

GMCs are around 15 to 600 light-years (5 to 200 parsecs) in diameter, with typical masses of 10 thousand to 10 million solar masses.[20] Whereas the average density in the solar vicinity is one particle per cubic centimeter, the average density of a GMC is a hundred to a thousand times lower. Although the Sun is much denser than a GMC, the volume of a GMC is so great that it contains much more mass than the Sun. The substructure of a GMC is a complex pattern of filaments, sheets, bubbles, and irregular clumps.[8]

Filaments are truly ubiquitous in the molecular cloud. Dense molecular filaments will fragment into gravitationally bound cores, most of which will evolve into stars. Continuous accretion of gas, geometrical bending, and magnetic fields may control the detailed fragmentation manner of the filaments. In supercritical filaments, observations have revealed quasi-periodic chains of dense cores with spacing of 0.15 parsec comparable to the filament inner width.[21] A substantial fraction of filaments contained prestellar and protostellar cores, supporting the important role of filaments in gravitationally bound core formation.[22]

The densest parts of the filaments and clumps are called molecular cores, while the densest molecular cores are called dense molecular cores and have densities in excess of 10^4 to 10^6 particles per cubic centimeter. Typical molecular cores are traced with CO and dense molecular cores are traced with ammonia. The concentration of dust within molecular cores is normally sufficient to block light from background stars so that they appear in silhouette as dark nebulae.[23]

GMCs are so large that local ones can cover a significant fraction of a constellation; thus they are often referred to by the name of that constellation, e.g. the Orion molecular cloud (OMC) or the Taurus molecular cloud (TMC). These local GMCs are arrayed in a ring in the neighborhood of the Sun coinciding with the Gould Belt.[24] The most massive collection of molecular clouds in the galaxy forms an asymmetrical ring about the galactic center at a radius of 120 parsecs; the largest component of this ring is the Sagittarius B2 complex. The Sagittarius region is chemically rich and is often used as an exemplar by astronomers searching for new molecules in interstellar space.[25]



Distribution of molecular gas in 30 merging galaxies.[26]

Small molecular clouds[edit]

Main article: Bok globule

Isolated gravitationally-bound small molecular clouds with masses less than a few hundred times that of the Sun are called Bok globules. The densest parts of small molecular clouds are equivalent to the molecular cores found in GMCs and are often included in the same studies.

High-latitude diffuse molecular clouds[edit]

Main article: Infrared cirrus

In 1984 IRAS[*clarification needed*] identified a new type of diffuse molecular cloud.[27] These were diffuse filamentary clouds that are visible at high galactic latitudes. These clouds have a typical density of 30 particles per cubic centimetre.[28]

Herbig Haro Objects

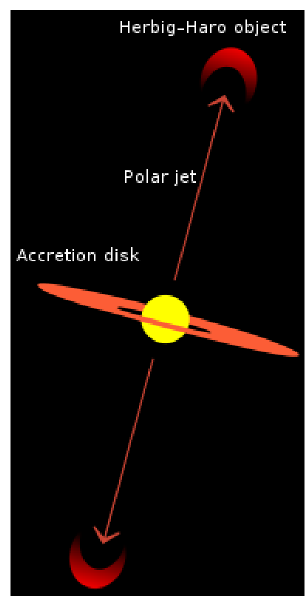
- bright patches of nebulosity associated with newborn stars.
- formed when narrow jets of partially ionized gas ejected by stars collide with nearby clouds of gas and dust at several hundred kilometers per second
- The jets interacting with and ionizing the interstellar medium causes the bright spectra that's observed
- commonly found in star-forming regions, and several are often seen around a single star, aligned with its rotational axis. (0 degrees from rotational axis)
- Most of them lie within about one parsec (3.26 light-years) of the source, although some have been observed several parsecs away. HH objects are transient phenomena that last around a few tens of thousands of years. They can change visibly over timescales of a few years as they move rapidly away from their parent star into the gas clouds of interstellar space (the interstellar medium or ISM). Hubble Space Telescope observations have revealed the complex evolution of HH objects over the period of a few years, as parts of the nebula fade while others brighten as they collide with the clumpy material of the interstellar medium

Electromagnetic emission from HH objects is caused when their associated shock waves collide with the interstellar medium, creating what is called the "terminal working surfaces".[11] The spectrum is continuous, but also has intense emission lines of neutral and ionized species.[7] Spectroscopic observations of HH objects' doppler shifts indicate velocities of several hundred kilometers per second, but the emission lines in those spectra are weaker than what would be expected from such high-speed collisions. This suggests that some of the material they are colliding with is also moving along the beam, although at a lower speed.[12][13] Spectroscopic observations of HH objects show they are moving away from the source stars at speeds of several hundred kilometers per second

- As they move away from the parent star, HH objects evolve significantly, varying in brightness on timescales of a few years. Individual compact knots or clumps within an object may brighten and fade or disappear entirely, while new knots have been seen to appear.[9][11] These arise likely because of the precession of their jets,[17][18] along with the pulsating and intermittent eruptions from their parent stars.[10] Faster jets catch up with earlier slower jets, creating the so-called "internal working surfaces", where streams of gas collide and generate shock waves and consequent emissions.[19]
- Short lived, typically formed in star-forming regions, associated with propstars

The total mass being ejected by stars to form typical HH objects is estimated to be of the order of 10^{-8} to 10^{-6} $M_\odot$ per year,[17] a very small amount of material compared to the mass of the stars themselves[20] but amounting to about 1–10% of the total mass accreted by the source stars in a year.[21] Mass loss tends to decrease with increasing age of the source.[22] The temperatures observed in HH objects are typically about 9,000–12,000 K,[23] similar to those found in other ionized nebulae such as H II regions and planetary nebulae.[24] Densities, on the other hand, are higher than in other nebulae, ranging from a few thousand to a few tens of thousands of particles per cm^3,[23] compared to a few thousand particles per cm^3 in most H II regions and planetary nebulae.[24]

Densities also decrease as the source evolves over time.[22] HH objects consist mostly of hydrogen and helium, which account for about 75% and 24% of their mass respectively. Around 1% of the mass of HH objects is made up of heavier chemical elements, including oxygen, sulfur, nitrogen, iron, calcium and magnesium. Abundances of these elements, determined from emission lines of respective ions, are generally similar to their cosmic abundances.[20] Many chemical compounds found in the surrounding interstellar medium, but not present in the source material, such as metal hydrides, are believed to have been produced by shock-induced chemical reactions.[8] Around 20–30% of the gas in HH objects is ionized near the source star, but this proportion decreases at increasing distances. This implies the material is ionized in the polar jet, and recombines as it moves away from the star, rather than being ionized by later collisions.[23] Shocking at the end of the jet can re-ionise some material, giving rise to bright "caps".[



HH objects are formed when accreted material is ejected by a protostar as ionized gas along the star's axis of rotation,

- Brightest ones are found at the end of jets from protostars
- All known Herbig-Haro objects have been found in regions of star formation
- Herbig-Haro objects are created due to the mass ejection from protostars in the form of jets. As the protostar gets older, the rate of mass loss decreases

Molecular Hydrogen Emission Line Object vs. Herbig-Haro Object:

- HH objects are observed in optical wavelengths, MHOs are observed in the near infrared

Herbig Ae/Be Star

- pre-main-sequence star – a young (<10 Myr) star of spectral types A or B.
- embedded in gas-dust envelopes and are sometimes accompanied by circumstellar disks.[1] Hydrogen and calcium emission lines are observed in their spectra.
- Circumstellar disks are formed when a protostellar cloud collapses because of conservation of angular momentum
- They are 2-8 Solar mass ($M_\odot$) objects, still existing in the star formation (gravitational contraction) stage and approaching the main sequence (i.e. they are not burning hydrogen in their center).
- In the Hertzsprung–Russell diagram, Herbig Ae/Be stars are located to the right of the main sequence.
- These have a shorter life span than T Tauri stars, so they're less studied than T Tauri

Protoplanetary Disks

- a rotating circumstellar disc of dense gas and dust surrounding a young newly formed star, a T Tauri star, or Herbig Ae/Be star.
- The protoplanetary disk may also be considered an accretion disk(a rotating disk of matter formed by accretion around a massive body, like blackhole, under the influence of gravitation) for the star itself, because gasses or other material may be falling from the inner edge of the disk onto the surface of the star. This process should not be confused with the accretion process thought to build up the planets themselves. Externally illuminated photo-evaporating protoplanetary disks are called proplyds.
- Protostars form from molecular clouds consisting primarily of molecular hydrogen. When a portion of a molecular cloud reaches a critical size, mass, or density, it begins to collapse under its own gravity. As this collapsing cloud, called a solar nebula, becomes denser, random gas motions originally present in the cloud average out in favor of the direction of the nebula's net angular momentum. Conservation of angular momentum causes the rotation to increase as the nebula radius decreases. This rotation causes the cloud to flatten out—much like forming a flat pizza out of dough—and take the form of a disk. This occurs because centripetal acceleration from the orbital motion resists the gravitational pull of the star only in the radial direction, but the cloud remains free to collapse in the axial direction.

Debris Disks

- a circumstellar disk of dust and debris in orbit around a star. Sometimes these disks contain prominent rings, as seen in the image of Fomalhaut on the right. Debris disks are found around stars with mature planetary systems, including at least one debris disk in orbit around an evolved neutron star.[1] Debris disks can also be produced and maintained as the remnants of collisions between planetesimals, otherwise known as asteroids and comets.
- Before planetesimals have enough gravity to accrete more mass, particles in the debris field are clumped together by electrostatic tensions
- If there's a star with a debris disk around it, you can infer there's at least one planet forming around it, there is at least one planet which already formed around it, or there was a failed proto-planet which could not fully form around it

Other Disk info:

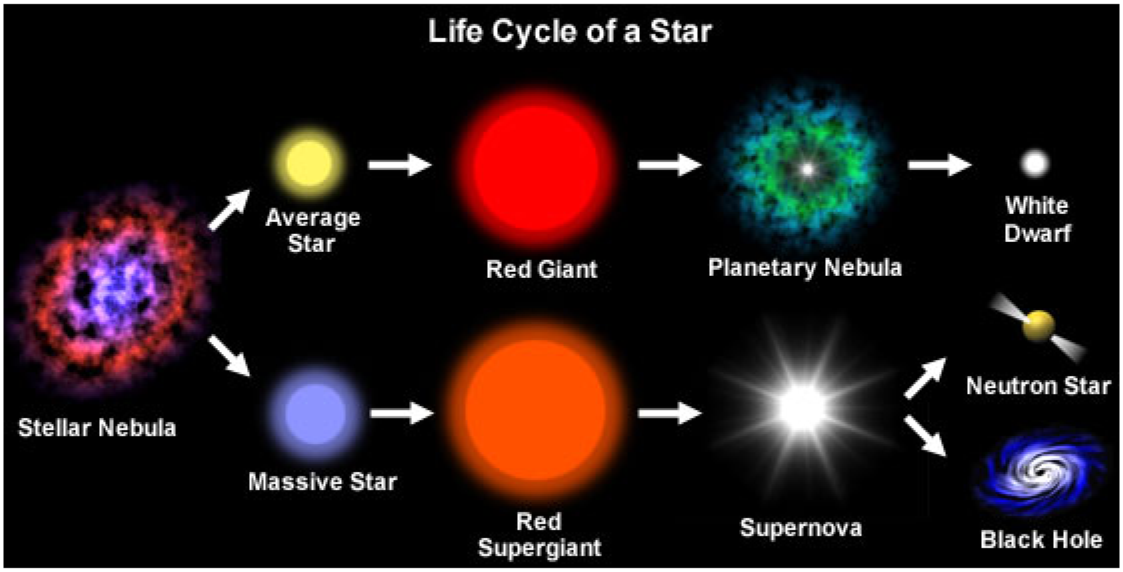
- Why many objects are spinning disks:
    - When a cloud of gas and dust collapses under gravity, it often possesses some initial rotation, which gives it angular momentum.
    - The motion in the directions orthogonal to the initial rotation tends to cancel out due to collisions and interactions among particles. This cancellation leads to the formation of a flatter spinning disk, where most of the mass ends up concentrated in this rotating plane. However, since angular momentum is conserved, the disk still spins.
- What causes shear forces in a protoplanetary disk
    - The material in the disk orbits around the center according to Kepler's Laws. This means that material that is farther away has a lower angular velocity.
    - This differential rotation means that within a region, the part closer to the center will orbit faster than the part farther from the center. This causes the region to "smear", resulting in the shear force.
- Within the disk, which force will dominate → The force with the shortest timescale will dominate.

HI and HII Regions:

- HI regions contain neutral, un-ionized hydrogen atoms and HII regions contain ionized hydrogen atoms
- HI region = cloud in the interstellar medium composed of neutral atomic hydrogen (HI), in addition to the local abundance of helium and other elements.
    - These regions do not emit detectable visible light (except in spectral lines from elements other than hydrogen) but are observed by the 21-cm (1,420 MHz) region spectral line.
    - This line has a very low transition probability, so it requires large amounts of hydrogen gas for it to be seen.
    - At ionization fronts, where HI regions collide with expanding ionized gas (such as an H II region), the latter glows brighter than it otherwise would.
    - The degree of ionization in an HI region is very small at around 10^{-4} (i.e. one particle in 10,000).
    - At typical interstellar pressures in galaxies like the Milky Way, HI regions are most stable at temperatures of either below 100 K or above several thousand K; gas between these temperatures heats or cools very quickly to reach one of the stable temperature regimes.
    - Within one of these phases, the gas is usually considered isothermal, except near an expanding H II region.

    - Near an expanding H II region is a dense HI region, separated from the undisturbed HI region by a shock front and from the H II region by an ionization front.
    - Mapping HI emissions with a radio telescope is a technique used for determining the structure of spiral galaxies. It is also used to map gravitational disruptions between galaxies.
    - When two galaxies collide, the material is pulled out in strands, allowing astronomers to determine which way the galaxies are moving.
    - HI regions effectively absorb photons that are energetic enough to ionize hydrogen, which requires an energy of 13.6 electron volts.
    - They are ubiquitous in the Milky Way galaxy, and the Lockman Hole is one of the few "windows" for clear observations of distant objects at extreme ultraviolet and soft x-ray wavelengths.
- An H II region or HII region is a region of interstellar atomic hydrogen that is ionized.
    - Evolve from molecular clouds
    - It is typically in a molecular cloud of partially ionized gas in which star formation has recently taken place, with a size ranging from one to hundreds of light years, and density from a few to about a million particles per cubic centimeter.
    - Ionization or recombination occurs because of star formation; in particular, the formation of young, hot, O/B type stars that have ionizing radiation
    - The Orion Nebula, now known to be an H II region, was observed in 1610 by Nicolas-Claude Fabri de Peiresc by telescope, the first such object discovered.
    - The regions may be of any shape because the distribution of the stars and gas inside them is irregular. The short-lived blue stars created in these regions emit copious amounts of ultraviolet light that ionize the surrounding gas.
    - H II regions—sometimes several hundred light-years across—are often associated with giant molecular clouds. They often appear clumpy and filamentary, sometimes showing intricate shapes such as the Horsehead Nebula.
    - H II regions may give birth to thousands of stars over a period of several million years. In the end, supernova explosions and strong stellar winds from the most massive stars in the resulting star cluster disperse the gasses of the H II region, leaving a cluster of stars which have formed.
    - H II regions can be observed at considerable distances in the universe, and the study of extragalactic H II regions is important in determining the distances and chemical composition of galaxies.
    - Spiral and irregular galaxies contain many H II regions, while elliptical galaxies are almost devoid of them. In spiral galaxies, including our Milky Way, H II regions are concentrated in the spiral arms, while in irregular galaxies they are distributed chaotically.
    - Some galaxies contain huge H II regions, which may contain tens of thousands of stars. Examples include the 30 Doradus region in the Large Magellanic Cloud and NGC 604 in the Triangulum Galaxy.
    - Eta Carinae is HII region

Life Cycle of a Star:



- Star will spend 90% of its lifetime in stage 2
- Initial mass determines how fast a star evolves
- Larger mass means shorter life span because resources get used up faster
- Close binary system with larger stars = shorter lifespan
- Nearly all the elements in the Universe are formed in the cores of massive stars except for hydrogen and helium (carbon, oxygen, silicon, sulfur, iron, and nickel are all formed in here)
- The outer layers of a star are more opaque than the layers closer to the core, which is why
- many stars have radiative transport in its inner layers since radiation isn't absorbed in outer layers

Birth:

- The life cycle differs between stars depending on their mass.
- Normal-mass stars begin in stellar nurseries, and some matter condenses to create a protostar.
- This gains more mass until fusion (H -> He) begins, when it becomes a main-sequence star.
- 0.8 solar masses is the lowest mass at which a star can begin hydrogen core fusion
- A solar nebula consists 98% of hydrogen and helium
- Star does NOT need to have a mass exceeding TOV limit, temperature below 1000 K, uniform magnetic field, or presence of heavy elements to start formation
    - The Tolman-Oppenheimer-Volkoff limit (TOV or Landau-Oppenheimer-Volkoff limit or LOV) is the maximum mass of a neutron star (around 3 solar masses)
    - Similar to Chandrasekhar Limit (max mass of a white dwarf)

Sun:

- When the sun was in its early solar system formation
    - It had a much faster rate of rotation than it does now

- It was NOT much more luminous than it is now and did NOT have a higher temperature than it does now
    - The solar wind was stronger back then than now
- Lithium burning is the process is responsible for removing the lithium from the sun
    - Occurs through p-p chain of nuclear reaction pathway

Moon:

- Formation of Earth;s moon likely resulted from a collision of two planetary embryos

Stellar nursery:

- A stellar nursery, also called a *molecular cloud*, is the cloud of matter from which stars originate.
- They are clouds primarily consisting of (molecular) hydrogen which are dense and big enough that molecules are formed from atoms.
- They are not extremely common in the interstellar medium (ISM), but they are the densest objects in it.
- Majority of hydrogen in ISM is considered to be HI
- The molecular gas found in the Milky Way corresponds with its spiral system.
- Most of the stellar nurseries that we see are **Giant Molecular Clouds (GMCs)**, which, predictably, are giant clouds of molecules.
    - They usually have masses upwards of 1000 solar masses and can be up to a few hundred light years across.
    - They are made up of complex systems of filaments, sheets, and bubbles, and the densest clouds can block light from stars in the background.
    - The Orion Nebula (M42) is part of the Orion Molecular Cloud (OMC), which is a well-known GMC close to our Sun.
    - Fragmentation is the process in which a giant molecular cloud breaks into many smaller pieces to begin star formation
    - When solar nebula collapses, rotation increases because of conservation of angular momentum
- Jeans mass is the term for the mass at which a gas cloud begins contracting into a protostar
- The cloud is unstable if it is either very massive at a given temperature or very cool at a given mass; under these circumstances, the gas pressure gradient cannot overcome gravitational force, and the cloud will collapse → called Jeans collapse criterion.
    - Magnetic field does NOT matter
- Gravitational potential energy is the dominant source of energy for star formation from a nebula/gas cloud

Protostar:

- When a star is in free-fall collapse, it is a protostar

- Protostellar cloud collapses under self-gravity, rotating solar nebula takes the shape of a disk, grain-sized particles stick together, large particles collide and form protoplanets and planetesimals, bombardment, present-day
- Its evolution revolves around the point that its energy comes from gravitational contraction.
- Due to its larger radius, it is more luminous than it will be on the main sequence.
- Its low temperature allows for high opacity; due to this high opacity, its main form of energy transport is convection.
- Protostars gradually shrink and gain material as their central temperature rises, then drops.
- As it contracts, it moves down on the H-R diagram. Its temperature doesn't change much at first, but when it rises, opacity decreases, allowing radiation to take over.
- When the star loses much energy to radiation, it moves to the left on the H-R diagram.
- Very low mass stars with masses less than 0.08 solar masses cannot reach the main sequence. → They may become brown dwarfs or, more rarely, planets.
- Protostars aren't found east of the Hayashi track because Collapsing protostars are supposed to be fully convective, and if a protostar is in that region, the protostar would not be stable, or in hydrostatic equilibrium.
- When mass accretion stops, the protostar is a pre-main sequence star (same energy source though)
- Some stars have no discernible pre-main sequence phase
    - Massive stars skip the pre-main sequence phase (or it's too short to be observable) → by the time they're visible, they're already fusing hydrogen
- Pre-main sequence stars are more luminous than main sequence

T Tauri Stars:

- pre-main-sequence variable stars that are contracting; spectral classes from F to M.
- They have many emission lines in their spectra, indicating their strong stellar winds.
- They are easy to identify and can be used as traces of solar-mass star formation regions.
- T Tauri stars almost always appear within dark dust clouds (Interstellar clouds + protoplanetary disks) and in binary systems
- T Tauri stars have masses generally less than 2 solar masses, with a relatively high lithium abundance.
- As a star ages, lithium is brought deeper into the interior, where it gets destroyed.
- Thus, the amount of lithium in a star can help give an estimation as to its age, with a higher lithium abundance implying a younger star.
- Type of variable and pre main sequence star (protostar) that uses gravity (gravitational energy) to power itself as it heads towards hydrogen fusion
- Expect to see strong lines of the Balmer Series
- Over 10 million years old
- Periodic variability (on timescale of days) → large sunspots cause this

- random fluctuations → accretion disk instability, obscuration by dust, or flares on star's surface cause this
- If 1 solar mass, star must develop a radiative zone for this for this stage of stellar evolution to end
    - Radiative zones are stable against the formation of convection cells
- If 4 solar masses, star is Herbig Ae/Be star
- If 10 solar mass, it's surprising to find star because Pre-main-sequence stars above 8 M evolve quickly and are on the main sequence by the time they disperse the surrounding dust cloud, so they aren't usually visible in their PMS stage

Main sequence:
- Stars spend the majority of their lives (about 80 percent) at this stage.
- The main sequence lifetime of a solar-mass star is approximately 10 billion years.
- How long a star remains on the main sequence depends on its mass.
- A star becomes a main sequence star when it is obtaining all its radiated energy from nuclear fusion of hydrogen into helium.
- The pressure that maintains hydrostatic equilibrium with gravity is exerted by collisions within the star.
    - When stars are in hydrostatic equilibrium, they do not move on the H-R diagram
- These collisions will eventually excite electrons in atoms, which then emit light waves.
- Some of these waves will escape the star; this lost energy comes at the price of lost random motion of atoms, which caused collisions in the first place.
- If nothing could replace this energy, the star would contract because pressure would decrease and gravity would take over.
- This is why thermonuclear reactions in the form of hydrogen burning must occur.
- Lower-mass stars burn hydrogen using the proton-proton chain. In this reaction, four hydrogen atoms combine to form a helium atom. The rate of this reaction is equal to
- T^4, where T is temperature.
    - M stars have the lowest temperature, so it has the longest main sequence lifetime
- Convection transfers heat across the outermost region of main sequence stars to the surface
- Convection is occurring in the outer layers, so we should see the areas of convection bubbling up and sinking around it, which is what creates the granular appearance
- More massive main sequence stars have higher temperatures
- Cooler main sequence stars tend to NOT have less spectral lines
- More than 99% of stars in the universe are main sequence stars
- The lower the mass of the star, the more stars there are with that mass (not just with main sequence stars)
    - HOWEVER the lower the mass, the less stars we observe with that mass
- Spectroscopic parallax → a technique that uses main-sequence fitting to determine a star's distance from Earth.

    - Uses spectra to determine distance of far away stars when you knew the distance of a close star
    - Might yield inaccurate distances for certain types of variable stars because their intrinsic luminosity changes over time
- Thermal pressure and radiation pressure are forces acting to stop the collapse of the star when it reaches main sequence
- Thermal pressure, radiation pressure, and electron degeneracy pressure are forces acting to stop the collapse of the sat in later evolutionary stages

Main Sequence to Red Giant:

- Energy released by the core collapsing from gravity drives outer layers to expand
- star transition across a typical H-R diagram during this phase; goes up and right
- hydrogen fusion moving from the core to the shell (used up all hydrogen fuel in the core) moves star off of main sequence

Red Giant to Horizontal Branch Phase:

- Helium Flash occurs in core that lets red giant transition into this phase
- This event is mostly undetectable; we wouldn't really observe anything
    - Because energy is used to bring the core out of degeneracy and excess energy is absorbed by outer layers
- Hydrogen and helium fusion keeps star from collapsing into itself
- Helium nuclei are fused into carbon during helium flash through triple-alpha process

Red Giant to Asymptotic Giant Branch:

- Fusion is occuring in a shell around the core; The core is collapsing, releasing energy (similar to red giant to horizontal branch)
- Outer layers cool because they are pushed outward when the helium shell around the core is violently re-ignited.
- A planetary nebula is formed from material expelled from a highly evolved low mass star. These outbursts may be a way that shells of material are expelled from the star.
    - At center of planetary nebula resides a white dwarf

Asymptotic Giant Branch:

- Stars in the asymptotic giant branch are short-lived. The degenerate core of the star is more massive that it was in the single-shell burning phase, and due to the peculiar nature of degenerate matter, the more massive core is physically smaller. The gravity experienced by overlying layers is hence stronger, requiring higher luminosities to maintain the balance between pressure and gravity. Thus the star expends energy at a very high rate and may well become a **red supergiant**. Stars in this phase of stellar evolution have proven to be challenging to model. One problem is that the helium shell burning is not stable. The layer of helium fusion is thin. Slight positive perturbations in the nuclear energy generate extra pressure and the region is enlarged slightly. But because the layer is thin, the change in height is slight and hence the change in pressure on the hotter region is changed very little. The higher temperature will likely increase the rate of nuclear reactions (many reaction processes are very temperature sensitive, such as the triple-alpha process which will most likely be dominant in the helium shell). Thus local reaction rates will pick up, generating more heat before it can diffuse

Maturity:

- When a main sequence star exhausts its core hydrogen, thermonuclear reactions cease.
- Gravity takes over and contracts the core.
- This heats the layer of hydrogen, so it can burn in a shell around the core in shell burning. This burning heats the surrounding areas, making them expand. Their temperatures decrease as their radii increase.
- The decrease in temperature increases opacity, resulting in convection taking over radiation again. The star's luminosity increases significantly.
- A helium core builds up inside the star, but there isn't enough heat/pressure to fuse the helium into heavier elements.
- However, the hydrogen "shell" around the helium core starts to fuse at a higher rate, causing the star to expand into a red giant and become more luminous.
- Then, as the star uses up its store of hydrogen, the outer layers of the star contract, finally achieving enough heat and pressure for the He in the core to fuse to carbon and oxygen.
- Helium burning occurs by the triple-alpha process. Because the gas in the core is degenerate, once it has been ignited, fusion spreads rapidly throughout the core.
- The temperature increases, increasing the rate of reactions, which then increases the temperature again in a cycle.
- This causes a helium flash when helium is suddenly ignited.
- After a slight contraction to heat the remaining helium, helium burning continues in a shell in a manner like that of hydrogen burning.
- The burning shells make the star expand enough to reach the red giant phase again, which it left after ceasing helium burning.
- Because the rate of the triple-alpha process is highly sensitive to temperature, the heat of the helium-burning shell makes the star unstable.
- The star will contract a little, increasing temperature, energy production, and pressure in the helium layer.
- The pressure increase overcompensates for gravity, so the star expands.
- This expansion then decreases the temperature, energy production, and pressure, so gravity contracts the star again. This continues in cycles known as thermal pulses.

Death:

- Normal-mass stars don't have enough mass to fuse carbon and oxygen into any heavier elements.
- During the thermal pulses, the star has a strong outflow of mass called a superwind.

- Once the star uses its entire store of hydrogen and helium, the outer layers of the star are ejected at high speed, potentially forming a planetary nebula.
    - UV Radiation from the central star ionizes the surrounding gas causes material in a planetary nebula to emit light
- The remaining carbon/oxygen core heats these layers, exciting photons so the nebula glows due to fluorescence.
- The core then cools to become a white dwarf (0.5-0.7M). A white dwarf will continue to shine bright despite no longer undergoing fusion, due to the leftover energy it radiates.
- In terms of Astronomy, the energy leftover from fusion is more than enough to keep the star bright for millions of years.
- If a white dwarf accumulates enough mass (perhaps gas from its partner in a binary system), it will explode in a Type Ia supernova.

White Dwarfs:

- The more massive the white dwarf, the bigger the radius
- Typically, has the mass of the sun and the volume of the Earth
- A white dwarf could collapse into a black hole if it accretes enough mass from a companion to exceed the Chandrasekhar Limit (1.44 solar masses)
    - Has to overcome Pauli Exclusion Principle for this to occur
- Stars with 8 or less solar masses turn into white dwarfs

Brown Dwarfs

- **have more mass than the biggest gas giant planets, but less than the least massive main-sequence stars. Their mass is approximately 13 to 80 times that of Jupiter (M_J)[2][3]—not big enough to sustain nuclear fusion of ordinary hydrogen (^1H) into helium in their cores, but massive enough to emit some light and heat from the fusion of deuterium (^2H). The most massive ones (> 65 M_J) can fuse lithium (^7Li).[3]**
- Appear diff colors to the naked eye depending on temperature
- They fuse deuterium, but most massive ones fuse lithium
- DBMM = Deuterium burning minimum mass
- brown dwarfs occupy types spectral types M, L, T, and Y based on surface temperature
- Brown dwarfs do not undergo stable hydrogen fusion, they cool down over time, progressively passing through later spectral types as they age.
- Black dwarfs are cooled down white dwarfs (after main sequence), while brown dwarfs are still main sequence stars
- Transition from spectral type L to T due to changes in temperature
- More chemically similar to red dwarfs than white dwarfs
- As brown dwarfs do not undergo stable hydrogen fusion, they cool down over time,
- progressively passing through later spectral types as they age.
- Their name comes not from the color of light they emit but from their falling between white dwarf stars and "dark" planets in size.

- The warmest ones are possibly orange or red, while cooler brown dwarfs would likely appear magenta or black to the human eye.
- Brown dwarfs may be fully convective, with no layers or chemical differentiation by depth.
- Though their existence was initially theorized in the 1960s, it was not until the mid-1990s that the first unambiguous brown dwarfs were discovered.
- As brown dwarfs have relatively low surface temperatures, they are not very bright at visible
- wavelengths, emitting most of their light in the infrared. However, with the advent of more capable infrared detecting devices, thousands of brown dwarfs have been identified.
- The nearest known brown dwarfs are located in the Luhman 16 system, a binary of L- and T-type brown dwarfs about 6.5 light-years (2.0 parsecs) from the Sun. Luhman 16 is the third closest system to the Sun after Alpha Centauri and Barnard's Star.
-

High Mass Stars:

- Larger stars are similar, except they begin with more mass and grow to supergiants.
- However, high-mass stars DO have enough mass to fuse carbon and oxygen into heavier elements, each step of which temporarily creates enough outwards pressure to keep the star from collapsing under its own mass.
- Fusion continues all the way to iron in a process known as nucleosynthesis. Any element heavier than iron releases energy through fission instead of fusion.
    - The s-process (slow neutron capture process) is primarily responsible for the creation of Intermediate and heavy elements beyond iron in the periodic table
- The energy released by fission isn't enough to support a star of such large mass, and evidence of fission indicates that a star will soon be approaching the end of their lifetime.
- You can’t get energy out of iron through fission or fusion due to iron having the lowest binding energy per atom of all the elements. Therefore, an iron core is chemically inert; the star will have no more energy with an iron core.

Death:

- At the end of their lifetime, they can undergo a massive explosion known as a Type II Supernova, resulting in their collapse into a neutron star or a black hole.
- Ironically, Higher-mass stars go through their life-cycle faster than their low-mass counterparts because the extra mass results in a faster rate of fusion.
- Neutron stars are extremely dense, and rotate at high speeds.
- A popular comparison for the density of neutron stars is condensing the mass of the human population into the size of a sugar cube. → 10^17 kg/m3
- As main sequence stars, high-mass stars produce energy through the CNO cycle.
- This form of hydrogen burning uses carbon, nitrogen, and oxygen as catalysts for the production of helium.

Low Mass Stars:

- Smaller mass stars (red dwarfs-[0.08 to 0.45M]) don't become giants.

- Due to a main sequence lifespan longer than the age of the universe, no evolved red dwarf has been observed.
- Some current models predict the red dwarf increasing in surface temperature while maintaining a constant radius, transforming them into blue dwarfs.
- Upon the termination of nuclear fusion, the blue dwarf will cool into a white dwarf and eventually cool into a black dwarf.
- In general, the mass of a star is inversely proportional to its lifespan - smaller stars (red dwarfs) live much longer than our own Sun (an "average" star), which in turn has a much longer lifespan than massive stars like Vega.
- Low mass stars fuse up to carbon and end as a white dwarf, while high mass stars fuse up to iron and end as neutron star or black holes
- Largest portion (by number) of stars in the Milky Way

Proton-Proton Chain & the Details on Nuclear Fusion:

- Proton-proton chain: chain of thermonuclear reactions that is the chief source of the energy radiated by the Sun and other cool main-sequence stars.
- four hydrogen nuclei (protons) are combined to form one helium nucleus
- 0.7 percent of the original mass is lost mainly by conversion into heat energy, but some energy escapes in the form of neutrinos (ν)
- $$\begin{aligned} {}^{1}H + {}^{1}H &\longrightarrow {}^{2}H + e^{+} + \nu \\ {}^{2}H + {}^{1}H &\longrightarrow {}^{3}He + \gamma. \end{aligned}$$
    - Or just $4H \rightarrow He + 2\nu$
    - four hydrogen atoms smashing together and creating a helium atom, two electrons, two neutrinos, and two highly energetic gamma-ray photons.
- Nuclear fusion: releases energy because the total mass of the resulting single nucleus is less than the mass of the two original nuclei.
    - Einstein’s equation (E=mc2), which says in part that mass and energy can be converted into each other, explains why this process occurs
- The main fusion process that provides the vast majority of the sun's energy is the proton-proton I (PPI) chain. There are two other branches of the PP chain (II and III) but these only account for around 15 percent of the thermonuclear fusion in the sun.
- Photons created thro p-p chain will struggle to escape the star's dense interior, however — taking over 30,000 years to move from the core to the surface.
- During this time the photons are undergoing a series of collisions, absorptions, and re-emissions, which 'downgrade' their energy to photons of visible light eventually radiated out by the photosphere.
- The PPI isn't the main fusion reaction in more massive stars than the sun, however. Instead, most of these stars' energy comes from the carbon-nitrogen-oxygen (CNO) cycle which requires the higher temperatures of more massive stars to get started.

- The energy generated by fusion serves a vital purpose within stars, providing the outward pressure that balances the ball of plasma against the inward force of gravity.
- When fusion ceases, so goes the outward pressure; this results in the collapse of the star and the swelling and loss of its outer layers.
- For stars larger than our sun, this gravitational collapse creates enough pressure to trigger the nuclear fusion of helium created by the main sequence lifetime in its core, fusing it to create carbon, neon and oxygen.
- When helium is exhausted, collapse occurs again triggering the fusion of even heavier elements.
- As this continues, the star develops an onion-like structure with lighter elements fusing in its outer layers and subsequently heavier elements being created towards the core.
- This progression of nuclear fusions ends even for the most massive stars when iron dominates the stellar core. This is because iron is an extremely stable element and stars aren't massive enough to trigger its fusion.
- When all nuclear fusion ceases, the star undergoes a final and catastrophic gravitational collapse → supernova
- shockwaves from the compressing iron core — which will eventually birth a neutron star or even a black hole — hit gas shed by the supernova triggering further nuclear fusion creating elements heavier than iron and radioactive materials as well as blasting out x-rays and gamma-rays.

CNO Cycle:

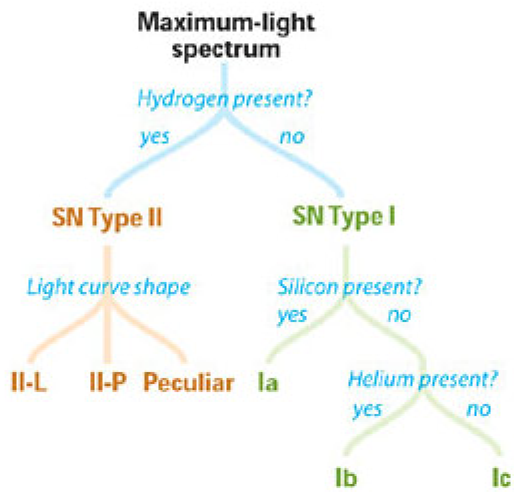
- sequence of thermonuclear reactions that provides most of the energy radiated by the hotter stars.
- It is only a minor source of energy for the Sun and does not operate at all in very cool stars.

$$
\begin{aligned}
{}^{12}C + {}^{1}H &\rightarrow {}^{13}N + \gamma \\
{}^{13}N &\rightarrow {}^{13}C + e^{+} \\
{}^{13}C + {}^{1}H &\rightarrow {}^{14}N + \gamma \\
{}^{14}N + {}^{1}H &\rightarrow {}^{15}O + \gamma \\
{}^{15}O &\rightarrow {}^{15}N + e^{+} \\
{}^{15}N + {}^{1}H &\rightarrow {}^{12}C + {}^{4}He + \gamma
\end{aligned}
$$

-
- C-12 is a catalyst

Supernovae:

- an event where a star explodes, destroying itself and releasing huge amounts of energy

- 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
- 

Phillips Relation:

- Relates peak luminosity and speed of luminosity evolution after maximum light

Core Collapse Supernova:

- Two ways to form supernova
    - thermonuclear explosion of a white dwarf which has been accreting matter from a companion is known as a Type Ia supernova,
    - core-collapse of massive stars produce Type II, Type Ib and Type Ic supernovae.
- Cutoff mass at which stars will end their lives in core-collapse supernovae = 8 solar masses
- For massive (>10 solar masses) stars, however, this is not the end. The contraction of the helium core raises the temperature sufficiently so that carbon burning can begin. After the carbon burning stage comes the neon burning, oxygen burning and silicon burning stages, each lasting a shorter period of time than the previous one. The end result of the silicon burning stage is the production of iron, and it is this process which spells the end for the star.
- Just before core-collapse, the interior of a massive star looks a little like an onion, with shells of successively lighter elements burning around an iron core. These burning stages become shorter and shorter as lighter elements are fused into heavier elements.
- Up until this stage, the enormous mass of the star has been supported against gravity by the energy released in fusing lighter elements into heavier ones. Iron, however, is the most stable element and must actually absorb energy in order to fuse into heavier elements. The formation of iron in the core therefore effectively concludes fusion processes and, with no energy to support it against gravity, the star begins to collapse in on itself.

- The collapse causes temperatures in the core to skyrocket, which releases very high-energy gamma rays. These photons undo hundreds of thousands of years of nuclear fusion by breaking the iron nuclei up into helium nuclei in a process called photodisintegration.
- At this stage the core has already contracted beyond the point of electron degeneracy, and as it continues contracting, protons and electrons are forced to combine to form neutrons. This process releases vast quantities of neutrinos carrying substantial amounts of energy, again causing the core to cool and contract even further.
- The contraction is finally halted once the density of the core exceeds the density at which neutrons and protons are packed together inside atomic nuclei. It is extremely difficult to compress matter beyond this point of nuclear density as the strong nuclear force becomes repulsive. Therefore, as the innermost parts of the collapsing core overshoot this mark, they slow in their contraction and ultimately rebound. This creates an outgoing shock wave which reverses the infalling motion of the material in the star and accelerates it outwards.
- Aiding in the propagation of this shock wave through the star are the neutrinos which are being created in massive quantities under the extreme conditions in the core. Under normal circumstances neutrinos interact very weakly with matter, but under the extreme densities of the collapsing core, a small fraction of them can become trapped behind the expanding shock wave. The energy of these trapped neutrinos increases the temperature and pressure behind the shock wave, which in turn gives it strength as it moves out through the star.
- The passage of this shock wave compresses the material in the star to such a degree that a whole new wave of nucleosynthesis occurs. These reactions produce many more elements including all the elements heavier than iron, a feat the star was unable to achieve during its lifetime.
- The creation of such elements requires an enormous input of energy and core-collapse supernovae are one of the very few places in the Universe where such energy is available. Eventually, after a few hours, the shock wave reaches the surface of the star and expels stellar material and newly created elements into the interstellar medium.
- Depending on the final mass of the core, neutron star, black hole, or nothing can be left after (no white dwarf)
- Spectrum of a core collapse supernova directly reflects the composition of the OUTER layer of the progenitor star
-

Type Ia Supernovae:

- Caused by white dwarves gaining too much mass from a binary companion and reaching the Chandrasekhar limit not by high mass stars reaching the end of their lives
- Also can be caused by two white dwarves colliding

- Generally occur in binary systems where a white dwarf pulls enough mass off of its companion to go supernova
- System that could cause white dwarf to go over the limit is a symbiotic Variable
- Limit is 1.4 solar masses; when it exceeds limit, it blows itself up in a supernova that's significantly brighter than Type II supernova
- Distinguished from other type I supernovae by the **presence of a strong silicon absorption line** in their spectra
- All type Ia supernovae emit roughly the same amount of energy and are the same brightness because they result from the same type of star (a carbon/oxygen white dwarf around 1.4 solar masses), making them a good tool to determine galaxy distances
- These supernovae also have very distinctive light curves that fall off quickly and steadily, as compared to the gradual fall-off of Type II supernovae
- The spectra is also distinctive, since exploding dwarfs **don't have hydrogen absorption lines**
- Type Ia is NOT a core-collapse supernova
- If you spot a Type 1a supernova, you'd be almost certain that there's a white dwarf located close by

Causes:

- Type Ia supernovae occur because of the Pauli Exclusion Principle, which states that two particles of the same type can't be in the same quantum state (position, velocity, energy level, spin, etc.)
- Quantum mechanics says that as a white dwarf gains mass and its electrons are squeezed into a smaller and smaller space, they have to move faster to avoid being in the same quantum state as other electrons
- As a white dwarf approaches 1.4 solar masses, its electrons start moving at nearly the speed of light!
- White dwarves are the most stable of stars
- They are very small
- They shed away their core- comprised of hydrogen and helium- and it turns into a planetary nebula
- Since nothing in the universe can move faster than the speed of light, a white dwarf can't exist above 1.4 solar masses, and instead collapses into a neutron star or a black hole
- This limit of about 1.4 solar masses is known as the Chandrasekhar Limit
- There are two main models for what can cause a Type Ia supernova: the single degenerate model and the double degenerate model.

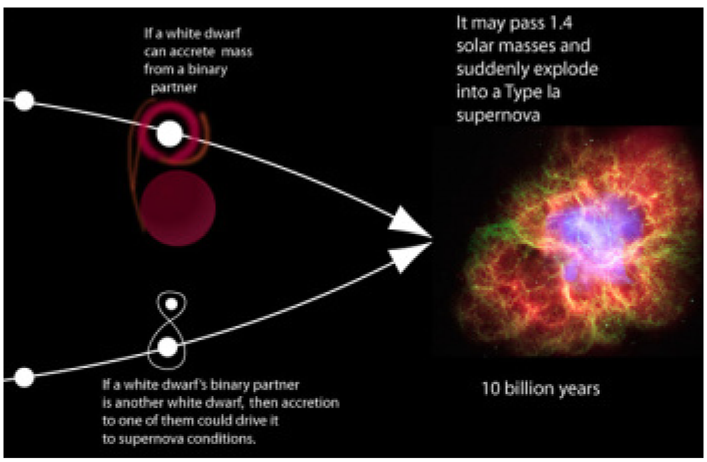
  Single Degenerate Model:

  - The most common model for a type 1a supernovae consists of a binary star system of two main sequence stars
  - (ejects about 1 solar mass worth of iron)

- The larger of the stars will expend the hydrogen in its core faster and evolve into a red giant before its partner
- Eventually, the larger star becomes a white dwarf and the smaller evolves into a red giant
- The orbital period of the binary star system then decreases and can be as low as a few hours
- As the angular momentum of the system is lost, the stars spiral together with the white dwarf accreting gas off of the red giant
- Ultimately, the white dwarf explodes for reasons listed above

Double Degenerate Model:

- Another model is where two white dwarves orbit each other quickly and begin to fall toward each other
- Eventually, they will collide in the center of the system, and the resulting body will have a mass of over 1.4 solar masses, thus exceeding the Chandrasekhar Limit and resulting in a supernova
- RX J0806.3+1527, a former DSO, fits this model



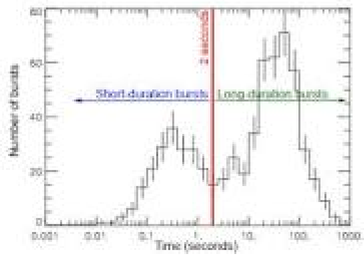
Exception to the Chandrasekhar Limit:

- There have been cases in which a white dwarf has exceeded the limit of 1.4 solar masses before exploding, and the most famous of these is SN 2003fg, nicknamed the "Champagne Supernova"
- This object approached a mass of 2 solar masses before exploding, so it is causing astronomers to question the universality of the Chandrasekhar Limit
- One hypothesis for the fact that it exceeded the mass is that its fast rotation allowed it to support more mass than normal white dwarfs

Identifying Type Ia Supernovae:

- Couple ways that can verify whether the object we are looking at is truly a Type Ia supernova

Gamma Ray Bursts:

- The fact that long Gamma ray bursts are isotropically distributed across the sky is supporting evidence that most of them are extragalactic and similar to supernovae in their astrophysical origin
- If you plotted a histogram of the burst durations of a catalog of Gamma Ray Bursts, you would see a bimodal distribution
- 

- Short-duration GRBs last less than 2 seconds and are thought to originate from neutron star mergers, while long-duration GRBs last more than 2 seconds and are believed to be the result of massive star collapse

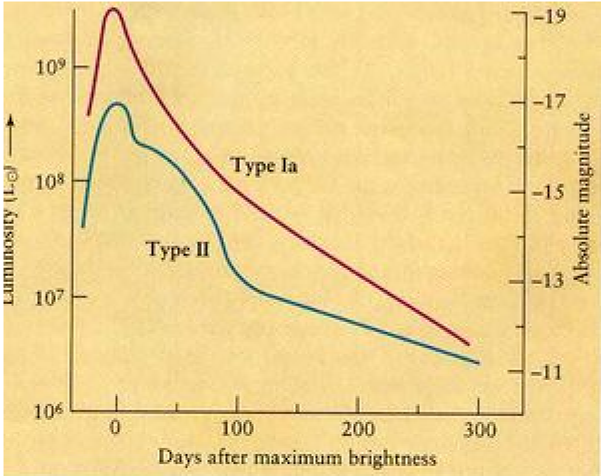
Kilonova:

A **kilonova** (also called a **macronova**) is a transient astronomical event that occurs in a compact binary system when two neutron stars or a neutron star and a black hole merge.[1] These mergers are thought to produce gamma-ray bursts and emit bright electromagnetic radiation, called "kilonovae", due to the radioactive decay of heavy r-process nuclei that are produced and ejected fairly isotropically during the merger process.[2] The measured high sphericity of the kilonova AT2017gfo at early epochs was deduced from the blackbody nature of its spectrum.[3]

- Two neutron stars merging produces a larger neutron star or a black hole

Light Curves:

- One of the ways astronomers identify Type Ia Supernovae is through their light curves
- All of the light curves have a similar shape, with a sharp increase, followed by a decrease that begins steeply and gets flatter
- Also, because Type Ia supernovae originate in the same basic way, they all have a peak absolute magnitude of around -19.3, which is useful as a standard candle
- This is one of the main ways that they are differentiated from Type II supernovae, whose curves have distinctly different shapes



Emission Spectra:

- All Type Ia supernovae also have very similar emission spectra, since they all originate from white dwarves
- The two major characteristics of Type Ia are that they are lacking in hydrogen (common to all Type I supernovae) and have strong Si II lines (only characteristic of Ia)

Use In Determining Distances:

- An important characteristic for Type Ia supernovae is that they can act as a standard candle
- All Type Ia supernovae have an absolute magnitude of about -19.3 (sometimes cited as -19.6), so by measuring the apparent magnitude observed from the explosion on Earth, one can simply use the distance modulus formula to determine the distance to the object.
- The distance modulus is given by: $m - M = 5(log(d) - 1)$; distance is in pc
- Since the absolute magnitude at the peak must be -19.3, you can substitute this into the equation as the value for M: $m + 19.3 = 5log(d) - 1)$
- Or, if the equation is rearranged to get distance on one side: $d = 10^{\frac{m+19.3}{5}+1}$
- So once you know how bright the supernovae appeared from Earth at its peak, you can then determine its distance fairly accurately.

Type II Supernovae:

- 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
- These are made of degenerate elementary particles and have infinite density; Their gravity is so great that at a certain distance, called the event horizon, not even light can escape

Electron Degeneracy Pressure:

- Electron Degeneracy Pressure is a direct result of the Pauli Exclusion Principle, which states that no two electrons can occupy the same quantum state at the same time
- Because of this, electrons that are packed very close together experience a force preventing them from getting any closer
- However, gravitational force continues to be directed inward, so the electron degeneracy pressure is directed against this to prevent a gravitational collapse
- As the gravity increases, electrons move to higher and higher energy levels to compensate, causing them to move faster than normal
- Dominant force counteracting gravity in some part of a solar-mass star during Red Giant (core) and white dwarf phases

Chandrasekhar Limit:

- There is a limit to which the electron degeneracy pressure can work
- Eventually, the gravity is too great for the electron degeneracy pressure to overcome, since eventually the electrons must be moving at or above the speed of light to balance it, which is impossible
- The mass at this point is around 1.44 solar masses, and this is what is known as the Chandrasekhar limit
- Above this limit, white dwarves will undergo gravitational collapse and result in a Type Ia supernova, but it can also cause the core of a massive star to collapse, triggering a Type II supernova

Cause:

- Type II Supernovae result from the collapse of massive stars, resulting from the collapse of the star's iron core
- This usually occurs once the star starts fusing silicone- the end product is iron, which burns through fission rather than fusion
- This results in the formation of a series of layers within the star
- When the iron core reaches the Chandrasekhar mass limit of about 1.4 solar masses, the electron degeneracy pressure (in layman's terms, the unwillingness of electrons to be squeezed into a smaller and smaller space) which had kept it from collapsing before then, isn't enough to hold the core up
- Protons and electrons in the core are forced together to form neutrons and neutrinos

- The neutrinos produce a huge outward force simply because there are so many of them (they don't usually interact with regular matter)
- The force can not be successively countered, and the star will implode and send off a shockwave that becomes the supernova explosion
- Meanwhile, the outer layers of the star fall inward, due to gravity, as the core collapses
- When the core stops collapsing because of neutron degeneracy pressure (compression of neutrons in the contracting core), the outer layers crash into the core and "bounce" outwards, creating a shock wave
- Along with the outward pressure from the neutrinos, this shock wave is what causes the star (except for the core) to blow itself apart in a Type II supernova
- "Massive" stars generally need to be at least eight solar masses to be categorized as such, though much more massive stars are known to exist
- The theoretical maximum mass for a star is defined through the Eddington limit, though there have been observed cases that seemingly break it
- The more massive the star, the faster it will go through the stages of fusion and eventually collapse
- Because massive stars are metal-rich (they're the only ones capable of even fusing and creating most metals), they tend to be Population I stars, located in Open Clusters, where there are younger and more metal heavy stars
- As a result, Type II Supernovae are generally thought to occur in Population I stars and Open Clusters.

Variations of Type II Supernovae:

- Type II Supernovae are categorized based on their light curves
- However, there are various characteristics that have been determined to be related to the variation of supernova they will undergo
- Type II-p supernovae are expected to occur from stars that are up to around 90 times the mass of the sun and have a high metallicity.
- Type II-L supernovae are expected to occur from stars of around the previous mass, but with a lower metallicity.
- Type II-n supernovae are supernovae that have narrow Hydrogen lines in their emission spectra.

Results of Type II Supernovae:

- The results of a Type II Supernova are either neutron stars or black holes along with a supernova remnant
- The energy and mass that make up a supernova remnant spread out and become a part of the interstellar medium, fueling the creation of new stellar objects
- In this way, supernovae contribute to the "life cycle" of the universe- as stars collapse and reach their ends, parts get recycled to help create new stars and objects

  Neutron Stars:

  - Stars with 8 or more solar masses turn into neutron stars

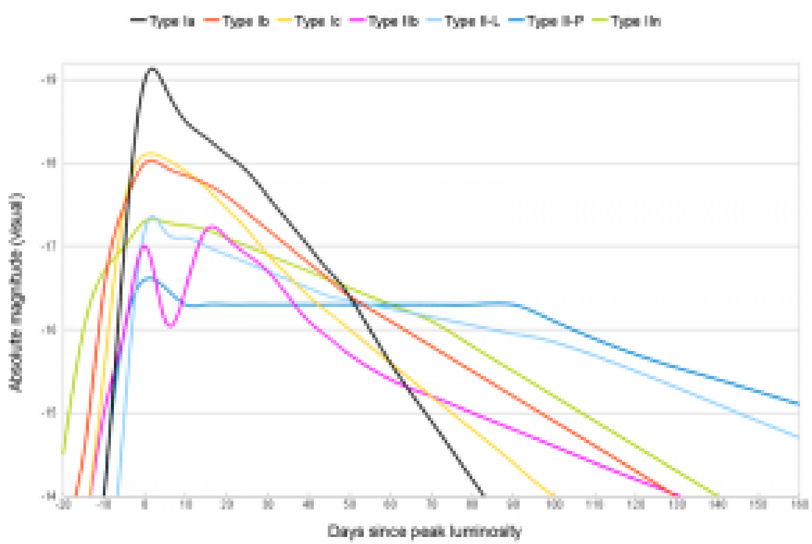
- If the core is 2-3 solar masses or less, it evolves into a neutron star - a star made up almost entirely of neutrons, leaving the star with no electrical charge
- Despite the name, neutron stars do not behave like normal stars in that they do not burn their core through fusion
- Neutron stars spin very fast due to how dense they are, and they have very strong magnetic fields, which can emit radio waves
- The angular momentum from the original star is conserved, but at a much smaller radius, causing its high rotational speed
- As these stars spin, the radio jets are aimed out into space
- When the jet is momentarily aimed towards Earth during its rotation, we see a regular, repeating pulse...which is why these stars are called pulsars
    - As neutron star slows or loses kinetic energy, radio bursts that scientists observe would be spaced out and they can use this to figure of the rate of loss of rotational kinetic energy in pulsars and neutron stars
- Neutron stars are composed of neutrons,
- Though there is no fusion, the star keeps itself together through degeneracy pressure
- This can be further explained by the Pauli Exclusion Principle, stating that no two subatomic particles can occupy the same place and state simultaneously
- Because of the Pauli Exclusion Principle, the neutrons repel each other and keep in motion, with the sheer number of neutrons creating a force that keeps the object together
- radius = 11 km; Mass = 1.3-2.5 Msun
- Carbon atmosphere and iron envelope on surface of star
- Neutron stars are the collapsed core of a massive supergiant which had a mass between 10-25 solar masses, more if the star was metal rich

Pulsars:

- Pulsars = rapidly rotating neutron star that emits regular pulses of radio waves and other electromagnetic radiation at rates of up to one thousand pulses per second
- Millisecond pulsars (MSPs) = pulsar with a rotational period less than about 10 milliseconds
    - origin of millisecond pulsars is that they are old, rapidly rotating neutron stars that have been spun up or "recycled" through accretion of matter from a companion star in a close binary system
- Magnetars = a neutron star with an extremely strong magnetic field.
    - Magnetars are differentiated from other neutron stars by having even stronger magnetic fields, and by rotating more slowly in comparison. Most magnetars rotate once every two to ten seconds, whereas typical neutron stars rotate one to ten times per second
- Oldest to Youngest → Magnetars, pulsars, MSPs

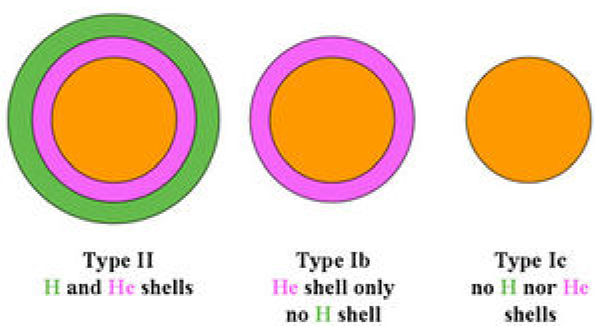
Light Curves:

- Light Curves relate to variable stars as well, but analyzing the light curves of supernovae can reveal information about them, such as their type or subtypes
- Type II Supernovae are primarily distinguished by a much slower decline in luminosity when compared to the days after the event, highlighted by a prolonged plateau
- Type II Supernovae also tend to peak lower than their Type I counterparts, in terms of luminosity
- Given the several different possible variations within the Type II supernova, it is important to know the differences between their light curves- it can end up being essential to their identification.
- Type II-p supernovae have the distinct plateau in their luminosity that type II supernovae are generally known for, showing a long period of constant luminosity before eventually fading down.
- Type II-L supernovae lack the plateau that Type II-p supernovae have, and are much more uncommon.
    - When asked to identify against a Type-I supernova, the Type II-L one will likely have a lower average magnitude and fade out after a much longer timespan.
- Type II-b supernovae are peculiar in that after a bit of time, they fade out similar to Type I-b supernovae
    - When identifying, look for a lower average magnitude and a change in the light curve similar to a "dip"- after declining in luminosity, the curve will rise and peak again, and decline in a (relatively) rapid fashion similar to a Type I supernova.
- Type II-n supernovae are a bit more luminous, peak a bit faster, and decline a bit faster, but nowhere near in the degree as Type I supernovae.



Type Ib and Type Ic Supernovae:

- Type Ib and Ic supernovae (also called stripped core-collapse supernovae) both result from the collapse of a massive star (like a population I star), much like Type II supernovae
- Type Ib happens when a star that has shed its hydrogen shell goes supernova.
- Type Ic loses hydrogen and helium shell
- However, since these stars have lost their outer layer of hydrogen before the explosion, hydrogen is absent from their emission spectra, so their spectra are comparable to Type Ia supernovae, which do not have hydrogen in them either
- Type Ic has also had its helium layer blown off, so it will not have helium lines in its spectrum either
- This blowing off of layers is normally caused by either a strong stellar wind by a partner in a binary system or the fact that the star is so massive that it has little gravitational control over its outer layers, as in a Wolf-Rayet star.
- Since, to exist, the parent stars of these supernovae must have been extremely large, they are only found in areas of rapid star formation, and so they are rarely found in elliptical galaxies and globular clusters.
- Like type Ia supernovae, they are characterized by a lack of hydrogen absorption lines in their spectra
- The spectra of Type Ib/c supernovae are very similar to that of a Type Ia, except for the fact that they **lack an absorption line of ionized silicon** at 635.5 nm
- The spectra of Types Ib and Ic can be distinguished by the absence of helium lines at 587.6 nm for a Type Ic (since it has lost most of its helium)



Planet Formation (Star Formation earlier):

- 51 Pegasi b. Is important → First exoplanet orbiting a sun-like Star/prototype of Hot Jupiter class of exoplanets
- Around PSR 1257 was where the first exoplanet was discovered by Aleksander Wolszczan
- Exoplanet is a planet outside our solar system
- Habitable planets are less likely to exist far from a galactic center because There are fewer metals to form planets in the outer disk

How planets form:

- The dust around a star is critical to forming celestial objects around it.
- Dust around stars contains elements such as carbon and iron which can help form planetary systems.
- When a star is in its forming disk, otherwise known as the T Tauri phase, it is ejecting extremely hot winds dominated by positively charged particles called protons and neutral helium atoms.
- Although much of the material from the disk is still falling on the star, small groups of lucky dust particles are crashing into one another, clumping into larger objects.
- Dust clumps become pebbles, pebbles become larger rocks that grind together to expand. The presence of gas helps particles of solid material stick together. Some break apart, but others hold on. These are the building blocks of planets, sometimes called "planetesimals."
- Where the disk is colder, far enough from the star that water can freeze, tiny fragments of ice hitch a ride with dust. Dirty snowballs can amass into giant planetary cores.
- These colder regions also allow gas molecules to slow down enough to be drawn onto a planet.
- This is how Jupiter, Saturn, Uranus and Neptune, the gas giants of our solar system, are thought to have formed. Jupiter and Saturn are thought to have formed first and quickly within the first 10 million years of the solar system.
- In the warmer parts of the disk, closer to the star, rocky planets begin to form.
- After the icy giants form there's not a lot of gas left for the terrestrial planets to accrete.
- Planets that are rocky like Mercury, Venus, Earth and Mars may take tens of millions of years to form after the birth of the star. The details of exactly where planets prefer to form in disks is still a mystery and an ongoing area of research.
- Once planets form around a star they are referred to as planetary systems, which are defined as sets of gravitationally bound objects that orbit a star.
- They can consist of one or more planets, but may also include dwarf planets, asteroids, natural satellites, meteoroids, and comets.
- The Sun and its planets, including Earth, is known as the solar system. The term "extrasolar" system and "exoplanet" system refer to planetary systems other than our own.

Stages:

- Dust to planetesimals → formation of planetesimals from dust via gravitational instability of the dust layer or binary coagulation of dust grains
- Planetesimals to protoplanets → grow by collisions
    - Initial growth mode is runaway growth, where larger planetesimals grow faster than smaller ones
    - When mass of protoplanets (runaway planetesimals) exceeds the critical mass, the growth mode shifts to oligarchic growth

    - Oligarchic growth → protoplanets grow in an orderly mode while maintaining orbital separation by orbital repulsion
    - As a result, by the end of the second stage, protoplanets are formed with orbital separations proportional to their Hill radii.
- Protoplanets to planets → known as giant impact phase where protoplanets collide with one another to form planets.

Planetary Formation Theories:
- Planetesimal hypothesis → theory of the origin of the solar system
    - Proposed by Forrest R. Moulton and Thomas C. Chamberlain in 1900
    - States that the planets were formed by the accumulation of extremely small bits of matter that revolved around the sun
    - This matter was produced when a passing star almost collided with the sun
    - During the near-collision, hot gasses were pulled out of both stars and the gasses then condensed
    - Planets were built up in hierarchical collisions
    - Greatest flaw as assuming matter would condense, but gravity was weaker so it probably won't
- Tidal theory → planets formed from condensed gasses "ripped" from an already existing Sun
    - James Jeans theory in 1917 that involved Sun and very massive star in 3 stages
    - 1. Massive star passes within Roche Limit of Sun, pulling out material in the form of a filament
        - Roche limit = distance at which a satellite begins to be tidally torn apart
    - 2. Filament is gravitationally unstable and breaks into series of blobs of masses greater than the Jeans' critical mass, and so collapse to form protoplanets
    - 3. Planets were left in orbit about the Sun
- Capture theory → during a close stellar encounter, Sun captures material out of which planets form
    - Modified version of Jeans' theory proposed in 1964 by M. Woolfson
    - Sun interacts with nearby protostar, dragging filament from protostar
    - Low rotation speed of Sun is explained as due to formation before planets
    - Terrestrial planets due to collisions between protoplanets close to Sun and giant planets
    - Planetary satellites due to condensation in drawn out filaments
- Nebula theory → planets formed at the same time as the Sun in the same gas cloud
    - Proposed by Pierre Laplace in 1796 and Consists of 5 stages
    - 1. Slowly rotating, collapsing gas and dust sphere.
    - 2. An oblate spheroid, flattened along the spin axis.
    - 3. The critical lenticular form - material in the equatorial region is in free orbit.

    - 4. Rings left behind in the equatorial plane due to further collapse. “Spasmodic” process leads to annular rings.
    - 5. One planet condenses in each ring with the Sun at center.

Stages of terrestrial planetary development (idk if this will be useful):

- Differentiation → layer formation
    - As a body becomes large enough to attract planetesimals en masse and become a planet, the energy generated by the frequent impacts begins a process of differentiation, whereby the material separates according to density.
    - Dense materials migrate to the core, attracted by gravity, whereas finer materials form the crust and early atmosphere.
    - The process is complex. Dense materials may separate out like drops of water and drop through the crust, while fluids and molten materials rise buoyantly through the crust, forming veins and fissures.
    - Differentiation happens because the system seeks to minimize gravitational energy.
- Cratering → Impacts and Scars
    - The crust of the newly formed planet eventually cools, but the bombardment of planetesimals that created it in the first place continues, and because the planet is no longer molten, the impacts form craters.
    - Some of the impacts may burst through the crust to the molten mantle.
    - In the early stages of planetary formation, the number of impacts is very high, as evidenced by Mercury and the moon, two bodies with old surfaces that have been largely unchanged since they were formed. Both planets are saturated with craters.
- Flooding → Lava covers everything
    - While cratering is still occurring -- and partly as the result of it -- the crust of a planet fractures, and lava bursts through and flows over the land, smoothing the craters and filling them.
    - In the case of Earth, water vapor also flowed through the fissures during this stage of planetary formation.
    - It rose into the atmosphere and fell to the ground as rain, forming the oceans and other bodies of water.
    - Water flooding didn't accompany lava flooding on other planets in the solar system. On these planets, the effects of lava flooding are more apparent.
- Surface evolution → changing landscape
    - The last stage of planetary formation, surface evolution, lasts for billions of years.
    - The face of the planet is slowly altered by the movement of tectonic plates and the effects of atmospheric movements and water.

- The collision of tectonic plates pushes up mountains and shifts continents, while rain and wind slowly wear away the surface and remove all traces of chaotic early stages of planetary formation.
- In the case of Earth, radioactivity in the core actually makes it hotter than it was when it formed, which may be one of many reasons why the conditions to support life evolved.

- In a multi-planet system, the phenomenon of orbital resonance can either stabilize or destabilize the system, depending on the specific orbital periods.

Detection of Exoplanets:

- In the equations below, the subscript s denotes the star, and the subscript e denotes the exoplanet. R denotes the radius of the object, and M denotes the mass of the object.

  Astrometry:
  - Least successful method of discovering exoplanets
  - the measurement of the positions, motions, and magnitudes of stars

  Transit:
  - Found the most exoplanets
  - The transit method uses the light blocked from the parent star by the host planet to determine various properties of the star and planet
  - When a planet comes across the plane of the star in the point of view of the Earth, the light given by the star will encounter a brief dip then flatten out before then coming back up to the mean value
  - This dip, called the transit depth, can be used to calculate the radius of the planet by comparing it with the radius of the star which can be determined through other means and the equation $\frac{\Delta F}{F_0} = \frac{R_p^2}{R_s^2}$ where ΔF is the change in flux or brightness of the star, and F_0 is the original flux
    - Transit depth relates to size/radius of exoplanet
  - When you want to observe the small dip in brightness as an exoplanet passes behind its host star, you look at the infrared spectrum
  - One important factor is the likelihood of transit in terms of the properties of the star
  - This also determines how likely it is to find a certain kind of exoplanet; The bigger the planet, the more likely the transit can happen which should make sense: the bigger the planet, the more area it covers in the sky and more importantly on the star itself, increasing the likelihood of a transit
  - The bigger the orbit, the less likely the transit can happen due to the inclination of the orbit

- With a smaller orbital radius, there exists a greater range of inclinations that can result in a transit regardless of the size of the planet
- However, with a larger orbital radius, there exists a lower range of inclination possibly resulting in a transit
- Multiple stars can be observed at once in search for exoplanets
- Best utilized for planets with “edge-on” orientation
- **Most planets discovered since 1995 (4150 planets maybe?)**
- Can be used to predict ingress and egress duration
    - Ingress = time it takes to fully cover star
    - Egress = time it takes to fully uncover star
- The main difficulty with the transit-photometry method is that in order for the photometric effect to be measured, a transit must occur. Not all planets orbiting other stars transit their stars as seen from Earth; a distant planet must pass directly between its star and Earth.
- Drawbacks: transit cannot be detected if the angle of inclination is near 90 degree; bigger orbit decreases probability of transit being viewed, smaller star decreases probability of transit being viewed.
- Does not allow a direct study of the discovered exoplanet
- We can observe a transit for Venus
- Based on the transit photometry curve alone, you can say these things could be true: system contains only 2 planets, or system contains more than 2 planets
    - You CAN’T say that the planets in the system are equal in size or that the system contains more than 1 central star (idk if this depends on a specific light curve though)

Radial Velocity:

- Found the second most exoplanets
- Requires precise spectroscopy, which is expensive, so not as many found as transit method
- Radial velocity, also known as Doppler spectroscopy, detects exoplanets by measuring Doppler shifts in the spectrum of the parent star. As of April 2016, about (1000 maybe?) of exoplanets were detected using radial velocity
- Can be used if the exoplanet’s orbital plane is along our line of sight (so a significant radial velocity can be measured) or if The exoplanet is also relatively large and close to its star.
- The velocity and period of the planet's orbit and the mass of the planet can be calculated after measurements with Radial Velocity
- First, if the mass of the star is not given, calculate it by plotting it on the H-R diagram

- If the velocity of the star is not given, calculate it using the doppler shift formula $\frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}$ where λ_0 is the average of the highest and lowest wavelength and $\Delta\lambda$ is the difference between the highest and the average wavelengths.
- Find the period P of the star's orbit from the radial velocity measurements. Then, use the general form $\frac{r^3}{P^2} = \frac{GM_s}{4\pi^2}$ of Kepler's Third Law, where r is the length of the semi-major axis of the planet's orbit. Alternatively, one can use the specific form $\frac{r^3}{P^2} = M_s$ where r is in AU, P is in years and M_s is in solar masses.
- Find the velocity of the planet using $v_p = \frac{2\pi r}{P}$
- Finally, find the mass of the planet using $m_s v_s = m_e v_e$; This calculation gives us the minimum mass of the planet. The measured velocity of the star is less than its true velocity if the orbital plane is not perpendicular to the sky
- Let α denote the orbital inclination, then the true velocity of the star and true mass of the planet is given by $v_{s,\,true} = \frac{v_s}{sin\alpha}$, $M_{e,\,true} = \frac{M_e}{sin\alpha}$
- When an exoplanet transits the parent star, the inclination is very close to 90 degrees. Therefore, the calculation based on radial velocity is close to its true mass.
- Using radial velocity and transit method, you can find the density of an exoplanet
- Disadvantage → Cannot accurately determine mass of planet; can only provide estimate of minimum mass/most likely to find types of planets least likely to be hosts of life.

Direct Imaging:

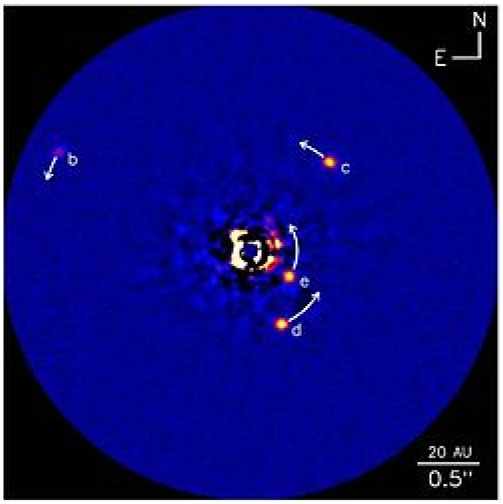
- Direct imaging detects exoplanets by resolving the exoplanet from the star in an image
- It's usually very difficult, because planets are much fainter than their parent stars
- The coronagraph is used to block the light from the star so the planets can be resolved
- Most direct imaged exoplanets are relatively close to the Earth, widely separated from its parent star, and are especially large and hot
- Images are made in the infrared, where the radiation from the planet is the strongest
- Can't use it if planet is close to luminous star because you can't see the planet over the star's light
- NOT TRUE → Attaining practical image quality requires one to be located very close to the system of interest, making it most useful for studying our solar system.

- NOT TRUE → Collecting sufficient data for analysis can take many months or even years since you need to plot the system's light curve over at least one period.
- The resolving power of the telescope must be very high to distinguish an exoplanet located far away.
- NOT TRUE → You must know the distance to the system of interest to ignore the effects of cosmological redshift.

Core Accretion Model

- a two-stage process whose first stage closely resembles the formation of terrestrial planets.
- A core with a mass of the order of 10 Earth masses forms in the disk by numerous collisions between planetesimals. Typically, there is not enough solid material to form bodies this massive in the inner region of a protoplanetary disk.
- At larger orbital radii, beyond the *snow line (frost line)*, the temperature is low enough that ice as well as rocky materials can condense. This extra solid material, together with the reduced gravity of the central star, allows large solid cores to form in the outer regions of a disk. Initially a core is surrounded by a low-mass atmosphere, which grows steadily more massive as the gas cools and contracts onto the core.
- Eventually the core exceeds a "critical core mass", beyond which a hydrostatic envelope cannot be maintained. Determining an accurate time scale for reaching the critical core mass is very difficult, in part because the rate at which the gas cools depends upon how transparent the envelope is. The transparency varies dramatically with the amount of dust present, which is extremely uncertain. Once the core mass is exceeded, gas begins to flow onto the core. It is slow at first but increases rapidly as the planet becomes more massive. Growth ceases when the supply of gas is terminated, either because the planet opens a gap in the disk or because the disk gas dissipates.
- Terrestrial planet formation will be found close to the central star where temperatures are high

- In short: The model proposes that gas giant planets form by the gradual accumulation of solid cores (or planetesimals) followed by the rapid accretion of surrounding gas from the protoplanetary disk.
- Terrestrial planets→ higher density, condense at higher temperatures and so they form closer to stars than gas giants because heavier elements are more strongly attached by a star



(Direct Image of 4 planets around the star HR 8799)

Gravitational Microlensing Method:

- Gravitational lensing is an observational effect that occurs because the presence of mass warps the fabric of space-time, sort of like the dent a bowling ball makes when set on a trampoline.
- Microlensing → relies on relativistic effects of gravity to bend light
- The effect is extreme around very massive objects, like black holes and entire galaxies.
- But even stars and planets cause a detectable degree of warping, called microlensing.
- Here's how it works. Light travels in a straight line, but if space-time is bent – which happens near something massive, like a star – light follows the curve. Any time two stars align closely from our vantage point, light from the more distant star curves as it travels through the warped space-time around the nearer star.
- If the alignment is especially close, the nearer star acts like a natural cosmic lens, magnifying light from the background star. Planets orbiting the lens star can produce a similar effect on a smaller scale.
- Roman will find planets in other poorly studied categories, too.
- Microlensing is best suited to finding worlds from the habitable zone of their star and farther out.
- This includes ice giants, like Uranus and Neptune in our solar system.
- While ice giants are a minority in our solar system, a 2016 study indicated that they may be the most common kind of planet throughout the galaxy.
- Roman will put that theory to the test and help us get a better understanding of which planetary characteristics are most prevalent.

Types of Exoplanets:

Gas Giant:

- Planet composed mainly of hydrogen and helium; may possibly have rocky or icy cores; masses greater than 10 Earth masses
- Around 25% of all discovered exoplanets are gas giants.

Hot Jupiters:

- Hot Jupiters are gas giants that orbit very close to its host star
- First type of exoplanet found
- Scientists believed Hot Jupiters formed farther away and migrated inward → describes formation of Hot Jupiters
- Migration is a change in orbit due to interactions with a disk of gas or planetesimals
- Hot Jupiters are found within .05-.5 AU of the host star
- Much, much larger high orbital velocity around its central star
- They are extremely hot, with temperatures as high as 2400 K
- They are the most common type of exoplanet found because they are the easiest to detect (because they are huge and close to the host star.)
- Around 50% of discovered exoplanets are Hot Jupiters.

Ice Giant:

- Composed primarily of volatile substances heavier than helium, such as oxygen, carbon, nitrogen, and sulfur
- Ice giants have significantly less helium and hydrogen than gas giants and they are also smaller
- Uranus and Neptune are ice giants
- According to some planetary models, these two giant planets may have layers of superionic ice under relatively shallow hydrogen and helium atmospheres, which would explain their unusual magnetic fields.
- H_2O, CH_4 and NH_3 abundant on these planets

Terrestrial Planet:

- Composed primarily of silicate minerals or metals

Super-Earth:

- Defined exclusively by mass with upper and lower limits, Super Earths are 'potentially' rocky planets with up to 10 times the mass of Earth
- The term 'Super Earth' simply refers to the mass of the planet and not to any planetary conditions, so some of these may actually be gas dwarfs
- The Kepler Mission defined a Super-Earth as a planet bigger than Earth-like planets (.8-1.25 Earth radii), but smaller than mini-Neptunes (2-4 Earth-radii).
- A super-Earth has a lower mass than a mini-Neptune; those two are classified solely by mass.

Mini-Neptune:

- Also known as a gas dwarf or transitional planet
- Mini-Neptunes are planets with a mass up to 10 Earth masses
- They are less massive than Uranus and Neptune (shocker) and have thick hydrogen/helium atmospheres.

Pulsar Planet:

- A planet that orbits a pulsar, a rapidly rotating neutron star
- Pulsar planets are discovered through anomalies in pulsar timing measurements
- Pulsars rotate at a regular speed, so any bodies orbiting the pulsar will cause regular changes in its pulsation
- The changes can be detected with precise timing measurements
- Pulsars were used to confirm the existence of extrasolar planets

Goldilocks Planet:
- Planet that falls within a star's habitable zone, which basically means it has liquid water.

Rogue Planet:
- Also known as interstellar planets, nomad planet, free-floating planet, orphan planet, wandering planet or starless planet
- A planet without a host star that orbits the galaxy directly.

Puffy Planet:
- A planet with a large radius but very low density
- Puffy planets expand because they are being warmed from the inside out
- This warming may be from the star's heat reaching the planet's core, or from stellar winds carrying ions and heat that reach deeper into the planet
- The ions are attracted to the planet's magnetic field
- Friction is generated by winds blowing past ions being held by the magnetic field, creating heat that will warm the planet from the inside and causing it to expand.

Chthonian Planet:
- The rocky core left behind when a hot Jupiter orbits too close to their star
- The star's heat and extreme gravity can rip away the planet's water or atmosphere.
- 0 have been detected so far

Water Worlds:
- An exoplanet completely covered in water
- Simulations suggest that these planets formed from ice-rich debris further from their host star
- As they migrated inward, the water melted and covered the planet in a giant ocean

Temperature of Exoplanets:
- In calculation of temperature of exoplanets, the star is often assumed to be a blackbody
- The exoplanet is assumed to reflect some of the radiation, have no heating from its core, and have emissivity close to 1
- Let the temperature of the exoplanet and the star be T_e and T_s, and the radius be R_e and R_s. They are separated by a distance of *D*. Then, by Stefan-Boltzmann Law, the radiation from the star and the exoplanet is $L_s = 4\pi R_s^2 * \sigma T_s^4$, $L_e = 4\pi R_e^2 * \sigma T_e^4$
- where σ is the Stefan-Boltzmann constant

- Only a fraction of the star's radiation reaches the exoplanet, and only a fraction of that radiation is absorbed. The ratio of radiation that reaches the exoplanet is $\frac{\pi R_e^2}{4\pi D^2}$ by considering the sphere centered at the sun that crosses the exoplanet, and $1 - A$ of those is absorbed, where A is the Albedo of the planet. Therefore, $L_e = \frac{\pi R_e^2(1-A)}{4\pi D^2} L_s$
- Expanding L_e and L_s and simplifying, we find $T_e^4 = \frac{R_s^2 T_s^4(1-A)}{4D^2}$, $T_e = \sqrt{\frac{R_s^2 T_s^4(1-A)}{4D^2}}$
- This equation can also be adjusted to account for the presence of an atmosphere with greenhouse gasses, which gives a better prediction of temperature for some types of exoplanets
- Summary: Need inverse square law for light at the planet's distance from the star, the albedo of the planet, and the atmospheric composition of the planet

Binary Star System:

- More massive star evolves faster
- Lower mass star would gravitationally pull some of the red giant's material from the outer layers onto itself when the faster evolving star expands to a red giant
    - This increases luminosity and temperature
- Primary factor used to classify binary star systems is orbital period
- Significant of a common proper motion → both stars more though space with the same velocity
    - Proper motion = The apparent angular motion of a star across the sky with respect to more distant stars, as seen from the center of mass of the solar system.
    - Parallax is caused by the motion of Earth around the sun, which is not taken into consideration in proper motion.
- Planets orbit both stars around a point called the barycenter

Triple star system:

- Two stars form a close binary system, while the third orbits at a greater system

Variable Stars:

- Stars that vary significantly in brightness with time, usually due to the buildup of energy via pressure generated from stellar processes.
- Changes in luminosity can be tracked via light curves, and periods may span from several hours to several years. Most lie on a strip (the instability strip) on the HR diagram between the main-sequence and red giants.
- Shortest to longest period: RR Lyrae, Cepheid, LPV (Mira); (LPV = long period variable)

Standard Candles:

- Astrophysical objects whose luminosity can be calibrated via measurements independ of flux and distance
- Usually known apparent magnitude
- Eg. helium flash red giant stars

Intrinsic Variable Stars:

- change in luminosity due to physical changes in the star

Pulsating Variable Stars:

- are stars whose atmospheres expand and contract periodically.

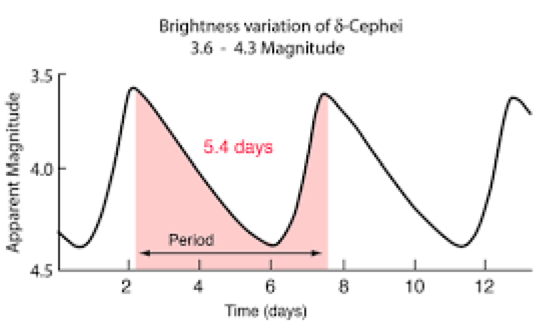
Wolf-rayet Stars:

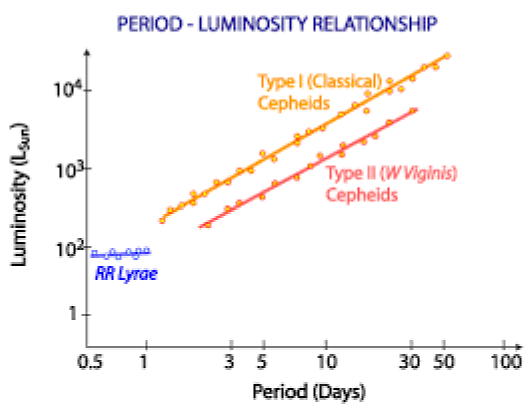
Wolf–Rayet stars, often abbreviated as WR stars, are a rare heterogeneous set of stars with unusual spectra showing prominent broad emission lines of ionized helium and highly ionized nitrogen or carbon. The spectra indicate very high surface enhancement of heavy elements, depletion of hydrogen, and strong stellar winds. The surface temperatures of known Wolf–Rayet stars range from 20,000 K to around 210,000 K, hotter than almost all other kinds of stars. They were previously called W-type stars referring to their spectral classification.

Classic (or population I) Wolf–Rayet stars are evolved, massive stars that have completely lost their outer hydrogen and are fusing helium or heavier elements in the core. A subset of the population I WR stars show hydrogen lines in their spectra and are known as WNh stars; they are young extremely massive stars still fusing hydrogen at the core, with helium and nitrogen exposed at the surface by strong mixing and radiation-driven mass loss. A separate group of stars with WR spectra are the central stars of planetary nebulae (CSPNe), post-asymptotic giant branch stars that were similar to the Sun while on the main sequence, but have now ceased fusion and shed their atmospheres to reveal a bare carbon-oxygen core.

All Wolf–Rayet stars are highly luminous objects due to their high temperatures

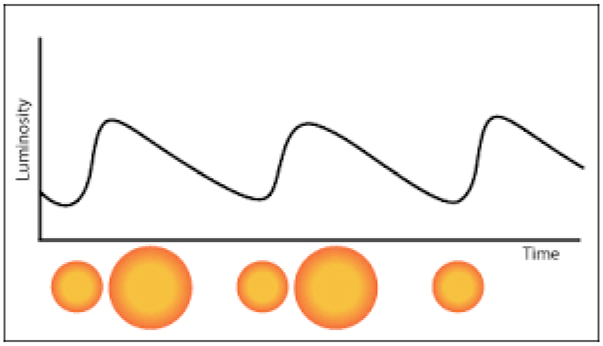
Cepheid variables:





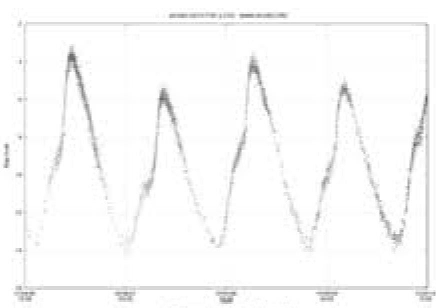
- have high luminosities and short periods, with their pulsation periods closely related to their luminosities.
- Stars which brightens and dims periodically
- Eg. RT Aurigae
- Cepheids are used as standard candles to establish distances because they have known absolute magnitude

    - Luminosity is dependent on period, and we can measure the period from any distance. Thus, we know the luminosity, and can then calculate the distance using apparent brightness.
- When the star expands outward, the temperature decreases and the luminosity increases



- They inhabit the upper portion of the instability strip on the HR diagram.
- They are based off of the star Delta Cephei.
- There are two classes of Cepheids: Classical and Type II.
- Type I Cepheids:
    - Type I Cepheids (δ Cepheus is a classical Cepheid) are population I stars with high metallicities, and pulsation periods generally less than 10 days.
    - Brighter and younger than type II
- Type II Cepheids:
    - Type II Cepheids (W Virginis stars), are low-metallicity, population II stars with pulsation periods between 10 and 100 days.

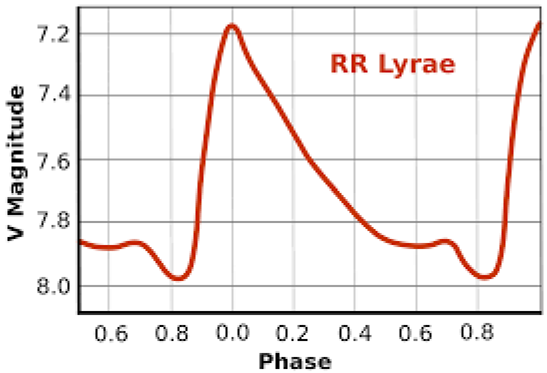
Mira variables:



- are red giant stars in the very late stages of stellar evolution (Asymptotic Giant Branch).
- This class of variable stars have pulsation periods of longer than 100 days with amplitudes greater than 1 magnitude in the infrared and 2.5 in the visible. Based off of the star Mira.
- They are rapidly losing mass which forms dust shrouds around the star
- Carbon rich and oxygen rich
- Semiregular Variable is similar to Mira Variables
    - We don't have any way of knowing the intrinsic luminosity of semiregular, as luminosity is not dependent on period.

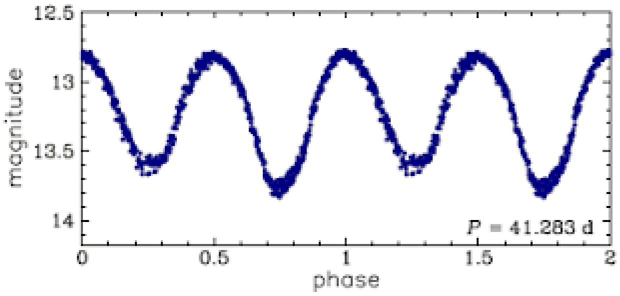
        - a type of variable star, is a giant or supergiant of intermediate and late spectral type showing considerable periodicity in its light changes, accompanied or sometimes interrupted by various irregularities
        - SRA vs SRB
        - SRA = consistent periodicities
        - SRB = inconsistent periodicities
    - CANNOT be used as Standard Candle

RR Lyrae variables:



- Can be used as standard candle
- are older, relatively low-mass, metal poor stars (Population II) with typical pulsation periods of less than one day, possibly as short as seven hours.
- Absolute magnitude around 0.75 (0-+5)
- They belong to a pulsating horizontal branch on the H-R diagram, and are usually class A or F stars with masses about half of that of the Sun.
- They are more common than Cepheids, yet are less luminous and are used as std. candles for relatively near objects and studies of globular clusters.
- Ionized helium is opaque, which allows the star to push outer layers out. if the helium is not opaque, then the outer layers will begin to fall inward until the helium is heated and ionized to opacity again. (causes pulsation in star)
- If the core of this star is generating more energy, it would take longer to make one pulsation because the helium would push out farther, then have to collapse farther back in, which would take longer.
- The luminosity of the star would increase with higher energy
- Red giant phase in stellar evolution
- Found in the galactic halo or bulge

T Tauri variables:

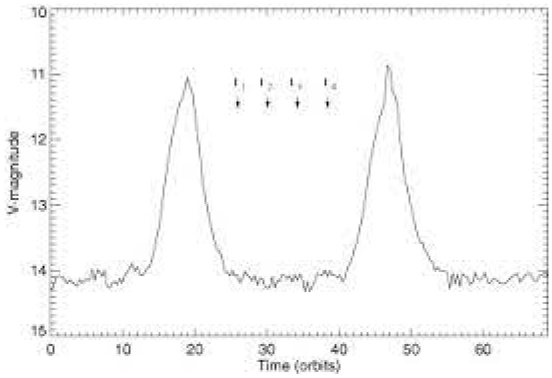


- are pre-main sequence stars and belong to F, G, K, and M classes.
- They are contracting along the Hayashi track to the main sequence, and display strong optical variability.
- Because of their large radii, they are more luminous than main-sequence stars of similar mass.
- Because of their youth, they are typically found near molecular clouds.

S Doradus variables:

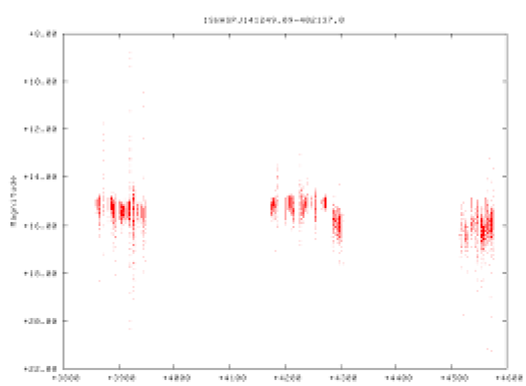
- are extremely rare, extremely massive, and extremely luminous stars.
- They are also known as Luminous Blue Variables and often show unpredictable and dramatic variations in both spectra and brightness that becomes an LBV is 21 M
- Minimum initial mass of main sequence star
- First published in the triangulum galaxy in 1922 by john charles duncan
- Are unstable supergiant or hypergiant stars with <1M years in the LBV phase.
- Temperatures can range from ~10,000K to 25,000K and luminosities range from 250,000-1M times that of the Sun. Example is Eta Carinae
- Lose mass because of stellar winds and random outburst
    - Luminosity will increase during these periods
- Brightness, spectral features, appearance, temperature all vary
- Type II supernovae comes next in stellar evolution
    - Core collapses when this happens
- Close to reaching the Humphreys-Davidson (HD) limit
    - sets the boundary between evolutionary channels of massive stars that either end their lives as red supergiants (RSGs) or as the hotter blue supergiants (BSGs) and Wolf-Rayet stars

Dwarf novae:



- are a class of cataclysmic variable stars consisting of a close binary system, one of which is a white dwarf accreting material from its partner.
- Collapse of accreted material causes a cataclysmic explosion.
- Have lower luminosities than classical novae and recur on scales from days to decades. Luminosity of outburst increases with interval and orbital period.
- Possibly useful as standard candles (used to measure distance because of its known luminosity)
- Look at the main sequence turnoff point and see how much it moved to estimate how much time passed from 2 HR Diagrams of Dwarf Novae and its previous binary system
- Faster evolving star = white dwarf; slower evolving star = red giant
- Buildup of mass on surface of white dwarf, common envelope (dust would make some variation), occasionally an outburst cause variations
- Dwarf novae, symbiotic stars, and X-ray binaries all have systems composed of a compact object and a non-compact donor star and they likely went through a common envelope phase

Eruptive Variable Stars:



- The second major type of intrinsic variable star are eruptive variable stars.
- These stars are mostly pre-main sequence stars, but an exceptional few main sequence stars are eruptive variables.

- Pre-main sequence (also called protostars) are stars that have not completed the process of becoming a main-sequence star from a gas nebula and are not yet condensed. So while condensing they change in magnitude.
- Eruptive Main-sequence variables are usually extremely larger or extremely smaller than the average main sequence star.
- Some eruptive variables are red giants since they easily lose their gasses.
- The last type of eruptive variable star is binary eruptive stars. These stars flare up and can remain that way for 1-4 years.
- Important eruptive variable stars are the Orion Variables, the Wolf-Rayet variables, and RS Canum Venaticorum variables.

Explosive Variable Stars:

- The third major type of an intrinsic variable star is a cataclysmic or explosive variable star.
- The most dramatic type of these variable stars are called Supernovae.
- This only occurs in extremely massive and old stars, or in white dwarfs that gain enough mass to go supernova.
- The outer layers of the star are expelled at high speeds creating a supernova remnant or nebula. A white dwarf or pulsar is usually left behind.
- The second type of these variables are called Novae. They are dramatic explosions caused by a pair of close binaries but don’t cause the total destruction of the star.
- Another type are dwarf novae and are very similar to novae. Dwarf novae are just two binary white dwarfs that regularly have outbursts.
- The fourth and final type of intrinsic variable are Z Andromedae Variables. These are a less common type of variable and are caused by a double star system containing a red giant and a hot blue star; enclosed in a cloud of dust and gas.

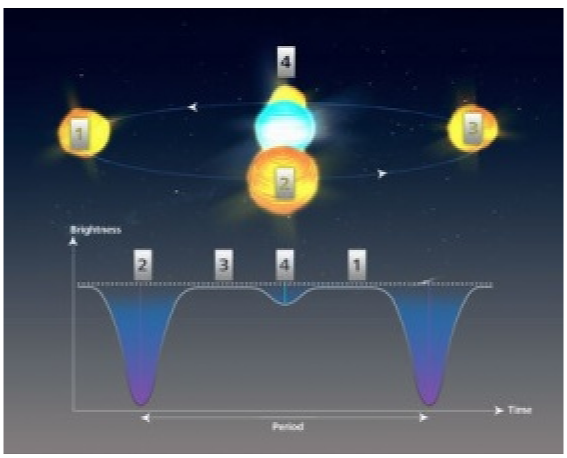
Extrinsic Variable Stars:

- Extrinsic variable stars can be stars that change in luminosity due to external changes; the two major types are rotating and eclipsing.
- Rotating variable stars are stars that change in luminosity due to the rotation of the star. This can happen because of such things as a sunspot on the surface as it rotates. This can also occur when two close binary stars change shape due to their mutual gravity. Fluctuations in magnetic fields can cause slight change in magnitude.
- The second type of extrinsic variable star are eclipsing variable stars. These are caused when stars in double star systems eclipse, causing a lowing of magnitude. However, this variation can only be viewed from certain angles. Planetary transits can also cause a very small variation in luminosity only viewed with very accurate instruments.

Binaries:

- A binary star system is a system of two stars that orbit a common center of gravity, or barycenter.

- These systems make up nearly 80 percent of all stars in the Milky Way. Binaries and other multiple-star systems can be visual, eclipsing, astrometric, spectroscopic, or a combination of these.
- Visual binaries appear to the unaided eye to be one star, but can be seen as two through a telescope. An example is Polaris, which is made up of Polaris A (which is two more stars in itself) and Polaris B.
- Eclipsing binaries appear to be single stars through a telescope; however, by measuring the brightness of an eclipsing binary, one can determine that the brightness changes over time.
- This change of brightness is because the plane of these stars' orbit lies along our line of sight. When one star passes in front of the other, it appears as though the "star" gets dimmer.
- If rings surrounding the central system are dusty material ejected by one of the stars, the star that produces the dust and stellar winds is typically a Wolf-Rayet Star
- If the dusty material is periodically compressed by stellar winds when they orbit close enough, the orbit of the binary system is highly eccentric
- Thus, their light curves reveal occasional dips in luminosity between constant periods due to this eclipse. Epsilon Aurigae, one of the DSO's, is a special eclipsing binary because one of its components is surrounded by a mysterious dust cloud.



- Spectral binaries are stars that are so close that they cannot be distinguished by either a telescope or by measuring brightness. They can only be separated with spectral analyses, which is where they get their names.

    - Herbig–Haro objects are bright patches of nebulosity associated with newborn stars. They are formed when narrow jets of partially ionized gas ejected by stars collide with nearby clouds of gas and dust at several hundred kilometers per second (found with T tauri stars) (found with infrared wavelengths)

X Ray Binaries:

X-ray binaries are a class of binary stars that are luminous in X-rays. The X-rays are produced by matter falling from one component, called the *donor* (usually a relatively normal star), to the other component, called the *accretor*, which is very compact: a neutron star or black hole. The infalling matter releases gravitational potential energy, up to several tenths of its rest mass, as X-rays. (Hydrogen fusion releases only about 0.7 percent of rest mass.) The lifetime and the mass-transfer rate in an X-ray binary depends on the evolutionary status of the donor star, the mass ratio between the stellar components, and their orbital separation.[1]

- Normal star + (white dwarf, neutron star, or black hole)

Blackbodys:

- A **black body** or **blackbody** is an idealized physical body that absorbs all incident electromagnetic radiation, regardless of frequency or angle of incidence. The name "black body" is given because it absorbs all colors of light. A black body also emits black-body radiation. In contrast, a **white body** is one with a "rough surface that reflects all incident rays completely and uniformly in all directions."[1]
- Has no reflectance so it appears white
- All moving baryonic matter emits electromagnetic radiation
- black body radiation is a continuous frequency spectrum only depending on a body's temperature
- Black holes are near perfect black bodies
- Radiation DOES NOT vary linearly with temperature

Globular Clusters:

A **globular cluster** is a spheroidal conglomeration of stars. Globular clusters are bound together by gravity, with a higher concentration of stars towards their centers.

Although one globular cluster, Omega Centauri, was observed in antiquity and long thought to be a star, recognition of the clusters' true nature came with the advent of telescopes in the 17th century. Using larger telescopes, 18th-century astronomers recognized that globular clusters are groups of many individual stars. Early in the 20th century the distribution of globular clusters in the sky was some of the first evidence that the Sun is far from the center of the Milky Way.

Globular clusters are found in nearly all galaxies. In spiral galaxies like the Milky Way they are mostly found in the outer spheroidal part of the galaxy – the galactic halo. They are the largest and most massive type of star cluster, tending to be older, denser, and composed of lower abundances of heavy elements (Population II) than open clusters (Population I), which are generally found in the disks of spiral galaxies. The Milky Way has more than 150 known globulars, and there may be many more.

The origin of globular clusters and their role in galactic evolution are unclear. Some are among the oldest objects in their galaxies and even the universe, constraining estimates of the universe's age. Star clusters were formerly thought to consist of stars that all formed at the same time from one star-forming nebula, but nearly all globular clusters contain stars that formed at different times, or that have differing compositions. Some clusters may have had multiple episodes of star formation, and some may be remnants of smaller galaxies captured by larger galaxies. Globular clusters are generally composed of hundreds of thousands of low-metal, old stars. The stars found in a globular cluster are similar to those in the bulge of a spiral galaxy but confined to a spheroid in which half the light is emitted within a radius of only a few to a few tens of parsecs.[32] They are free of gas and dust[46] and it is presumed that all the gas and dust was long ago either turned into stars or blown out of the cluster by the massive first-generation stars.[32]

- All stars in a globular cluster are around the same age and have similar compositions
- First one was NGC 104
- Relatively few supernovae (type II), planetary nebulae, luminous blue variables, and magnetars occur in globular clusters
- In Milky Way, typical globular cluster has Population II stars
-

Stellar Populations:

- Populations of stars are classified by their metallicity, or by how much heavy metals a star has.
- Higher metallicity of the universe when the star formed causes spectral differences between the populations
- Similar Chemical composition and age

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.
- Main factor that causes spectral difference between population I and II stars is the higher metallicity of the universe when the star formed
- hotter

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.
- Cooler
- Lower metallicity results in fewer massive stars, giving the galaxy a redder appearance
- due to older, cooler stars.

Population III (hypothetical):

- consisting 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

Emission Lines:

- If a particle emitting that emission line is traveling towards you, 1. The emission line shifts to higher wavelengths. 2. The emission line broadens

Galaxies:

- A galaxy is a gravitationally bound group of stars, dust and stellar remnants.
- Tully-fisher relation → technique that uses the rotational velocity of a galaxy to determine its distance from Earth

Galactic Structures:

- There are four main structures that may be found in galaxies: the disk, the halo, the bulge, and the nucleus.

Disk:

- This is the flattened area of a galaxy that surrounds the galactic bulge.
- It contains a majority of the luminous stars and interstellar matter (gas and dust in and amongst the stars).
- It contains both young and old stars, but has the highest quantity of young stars of these structures and is undergoing star formation.
- Stars move in circular orbits in the galactic plane of the disk.

Halo:

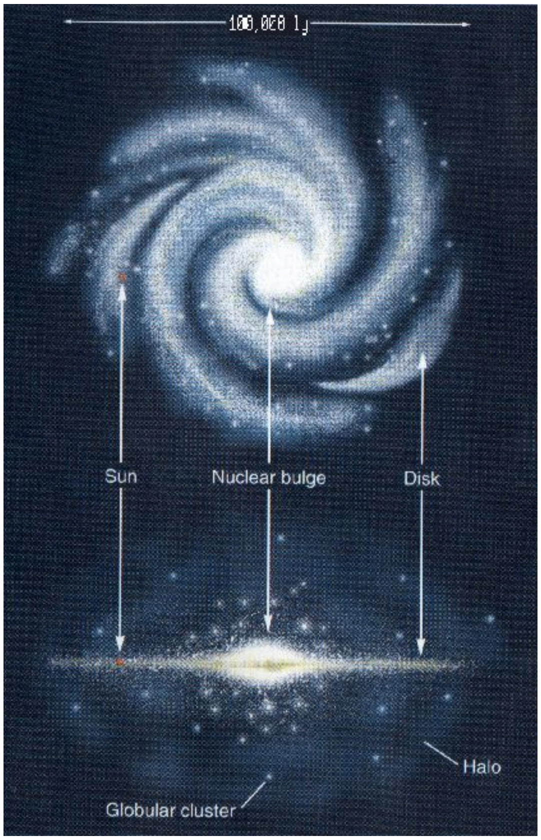
- This is the spherical area all around the galaxy.
- It is relatively dim, and contains only old stars.
- It does not contain interstellar medium, and is not undergoing star formation.
- The galactic halo contains a majority of the globular clusters.
- It appears reddish in color.
- Stars in the halo move in random orbits (in three dimensions).

Bulge:

- This is the area of a galaxy where the disk bulges in the center.
- It contains young and old stars, with a higher number of old stars toward the outer region of the bulge.
- It has ongoing star formation, especially toward the center, and has interstellar medium, in higher quantity toward the center.
- It appears yellow-white.
- Stars in the bulge have random orbits (in three dimensions)

Nucleus:

- This is the dense center of the galaxy, often contained within the bulge.
- It has a high density of stars and interstellar matter.



Hubble Classification:

- Edwin Hubble (American astronomer) was the first astronomer to categorize galaxies in a comprehensive manner, based heavily on their shape and structure.

Spiral Galaxies:

- Spiral galaxies are denoted by the letter "S" in the Hubble classification scheme.
- Spiral galaxies consist of an inner core of old stars moving slowly and outer arms of faster-moving younger stars.
- Spiral galaxies contain a flattened disk with apparent spiral arms, a dense bulge, and a halo.
- The bulge has the highest stellar density (stars per unit volume) in spiral galaxies.
- The disks of spiral galaxies are rich in interstellar matter.
- A high amount of star formation occurs in their spiral arms, which contain emission nebulae.
- Newly formed O and B-type stars cause the spiral arms to appear bluer than the rest of the galaxy.
- Spiral galaxies are classified into three subtypes, Sa, Sb, and Sc. Some major differences between Sa spiral galaxies and Sc spiral galaxies are listed in the table below, with Sb being an intermediate between the two in all categories.

	Sa	Sc
Appearance	More tightly wrapped spiral arms, almost circular in appearance.	More open, loose, poorly defined spiral arms. Displays knotty (or clumped) structure.
Bulge	Typically the largest bulge of the three types.	Typically the smallest bulge of the three types.
Interstellar Matter	Least quantity of interstellar matter of the three types.	Highest quantity of interstellar matter of the three types.

Barred Spiral Galaxies:

- Barred Spiral Galaxies are a variation of Spiral Galaxies, and are denoted by "SB" in the Hubble Classification Scheme.
- They have very similar properties to spiral galaxies, but have a horizontal bar of stars protruding out from the galactic core into the disk, and the spiral arms project from the ends of the bar.
- The subclasses (SBa-SBc) have the same properties as spiral galaxies in their classification.

Elliptical Galaxies:

- Elliptical galaxies are denoted by the letter "E" in the Hubble Classification Scheme.
- Elliptical Galaxies are generally older and larger than spiral galaxies.
- They display little structure of any type, with a dense nucleus in the center and halo surrounding it.
- Contain more Population II stars than the Milky Way
- They tend to not display a galactic bulge or disk, and it is very weak if they do.
- Elliptical galaxies contain very little cool interstellar matter, and there is no evidence of ongoing star formation or young stars.
- Elliptical galaxies contain mostly old, red stars.
- However, elliptical galaxies do contain large amounts of very hot interstellar gas.
- Elliptical galaxies have a huge variation.

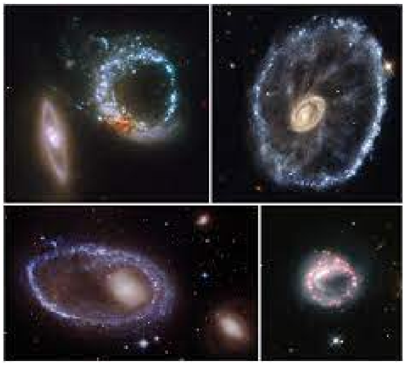
- They range from huge in size (giant ellipticals) to very small in size (dwarf ellipticals). In the Hubble Classification Scheme, they are ordered in terms of eccentricity.
- E0 ellipticals are perfectly circular, and E7 ellipticals cigar-shaped.

Lenticular Galaxies:

- This is a type of galaxy between an elliptical galaxy and a spiral galaxy.
- It contains a thin disk and bulge, but no gas or spiral arms.
- These galaxies are classified as S0 galaxies (or SB0 if they have a bar).

Irregular Galaxies:

- Irregular galaxies are denoted by "Irr" in the Hubble Classification Scheme.
- Their appearance does not fit them into any other category, and they tend to exhibit little to no internal structure.
- They tend to have lots of interstellar matter and young, blue stars.
- Irregular galaxies also have subclasses.
- The more common Irr I irregulars look more like misshapen spiral galaxies.
- The much rarer Irr II galaxies have a much more irregular shape, and commonly have an explosive or filamentary appearance.



Formation and Evolution:

- Studies on galaxy formation and evolution, unlike star formation and evolution, are still very young and in the early stages.
- There are some widespread theories that have gained popularity, however, of galaxy formation and evolution.
- Galaxy mergers do not inhibit star formation? (at least not because of the chaotic flow of dust and gas)

Formation:

- Galaxies likely are a result of slight differences in density in the early universe.
- Places with higher density would get matter pulled toward them through gravity, while places with lower density would have matter pulled away from them.
- These galaxies may have merged and grown to form the large galaxies we see today.

Evolution:

- Galaxies can evolve in two ways.
- They can evolve passively (without outside influence of other galaxies) or, much more commonly through interaction.

Passive Evolution:

- A galaxy's overall color, composition, and appearance will change as stars evolve and interstellar matter gets used up, and recycled through star death.
- The already red elliptical galaxies will likely get redder and fainter.
- The blue spiral and irregular galaxies will stay blue as long as gas remains are available for them to reform.

Interaction:

- Galaxies can interact to change in their entire internal structure, which can trigger star formation or cause activity in the galactic nucleus.

Galactic Interactions:

- Galaxies can interact with each other gravitationally in many ways.
- The most common is a near miss, where two galaxies pass each other nearly.
- The matter in both galaxies is gravitationally pulled together and the two galaxies begin to change structure, even from afar.
- This likely results in the galaxies returning together to merge.

- If the merger of galaxies was between a small and large galaxy, it is called galactic cannibalism, and the structure of the larger galaxy is likely to remain mostly unaffected.
- On the other hand, if the merger is between two galaxies of similar size, it results in a dramatic change in both galaxies (if both were spirals, it will likely end in an elliptical galaxy).

Dark Matter:

- Measurements of mass in space can sometimes not match up with the amount of mass we can actually see, and by a significant amount.
- One theory to explain this extra matter in the universe classifies the extra matter as Dark Matter, because we cannot see it in any wavelengths.
- We can only measure dark matter by the gravitational effect it has on normal matter.
- Otherwise, however, dark matter does not appear to interact with normal matter.
- While dark matter is dispersed throughout the universe, it specifically can affect how matter in galaxies interacts, and it can affect the motion of the galaxy.

Galaxy Groups and Clusters:

Galaxy Groups:

- Galaxies are usually located close to other galaxies.
- A galaxy group is the smallest group classification, and it refers to a group of about 30-50 galaxies.
- The Milky Way is located in the Local Group, along with the Andromeda and Triangulum Galaxies.

Galaxy Clusters:

- Galaxy clusters are larger than galaxy groups, containing hundreds to thousands of galaxies.
- They are among the largest known gravitationally bound systems in the universe.
- Galaxy clusters are massive systems that get around 1% of their mass from the galaxies in them.
- Around 9% of the mass comes from extremely hot gas (typically millions of Kelvins) very bright in X-Rays.
- Clusters typically consist of around 90% dark matter, observed through gravitational interactions such as gravitational lensing (the bending of spacetime, causing light to be bent around an object, and a background object to appear magnified, distorted, in different areas of the sky, and/or multiple times.
- Galaxy clusters are largely closed systems, and can be used to observe processes that happen in the universe (such as nucleosynthesis) on a smaller scale.
- Additionally, galaxy clusters tend to evolve very slowly, providing a probe to observe galaxy evolution.
- Galaxy cluster collisions are some of the most energetic events in the universe.

- Galaxy Clusters are formed because of very slight variations in density in the early universe.
- As the universe continued to expand, and the space between objects increased, more and more matter was attracted toward these denser spots, eventually becoming a galaxy cluster.

Galaxy Superclusters:

- The largest classification is that of galaxy superclusters, which are groups of other groups and clusters.
- They are massive, and span hundreds of millions of light years.
- They typically contain 3-10 galaxy clusters. The Milky Way is located in the Virgo (or Local) Supercluster.

Starburst Galaxies:

- A starburst galaxy is a term used to refer to any galaxy with a star formation rate up to 100 times greater than a normal galaxy.
- This rate is high enough that if this rate were to persist in the long-term, the star's reserves of gas would deplete in a small fraction of the galaxy's lifetime.
- For this reason, most starburst galaxies only stay that way for a short period of time.
- Starburst activity frequently arises when two or more galaxies interact with each other.
- Starburst galaxies are responsible for a sizable fraction of the universe's star formation.
- The high activity areas can be spread throughout the galaxy, or concentrated in a small area.
- Typically, starbursts are observed around the nucleus of a galaxy.
- Starburst galaxies are defined by three factors:
    - The rate that gas is being converted into stars (star formation rate or SFR)
    - How much gas is available
    - How long it will take to consume the available gas at the current star formation rate

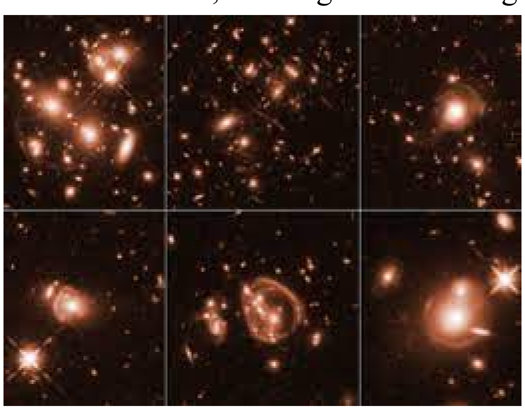
Types:

Blue Compact Galaxies (BCGs):

- Blue compact galaxies (BCGs) often have very low masses and no dust.
- They also have a very low metal content and are often blue in color.
- Most BCGs show signs of merging or close interactions, and they can be of any age.
- Blue compact dwarf galaxies are small BCGS, and Green Pea galaxies are small compact galaxies resembling starbursts.
- They are oxygen-rich, and no more than 16,300 light-years across.
- Green Peas are exclusively star-forming rather than having a nucleus.
- Green Peas are considered relatively rare objects.

Luminous infrared galaxies:

- Luminous infrared galaxies (LIRGs) are galaxies with luminosities over 1011 L⊙.
- They can also be referred to as submillimeter galaxies (SMGs), though they are typically known as LIRGs because of the large amount of infrared light they emit.
- These galaxies typically create around 100 new stars a year, which results in the high level of infrared light.
- However, this may also be caused by an active galactic nucleus (AGN).
- An AGN is a region at the center of a galaxy which has a very high luminosity, such as a quasar.
- LIRGs were discovered in 1983 by the Infrared Astronomical Satellite (IRAS).
- LIRGs emit around as much energy as quasars, but as they are not visible to the naked eye it is harder to detect them.
- LIRGs are brighter in the infrared because much of the visible light they give off is absorbed, resulting in it being given off as infrared thermal energy.
- Luminous infrared galaxies are also capable of becoming ultraluminous infrared galaxies (ULIRGs) when their luminosity surpasses 1012 L⊙.
- However, not all galaxies undergo this transformation.



Wolf-Rayet galaxies + Stars:

- Wolf–Rayet stars, often abbreviated as WR stars, are a rare heterogeneous set of stars with unusual spectra showing prominent broad emission lines of ionized **helium** and highly ionized **nitrogen** or **carbon**.

- The spectra indicate very high surface enhancement of heavy elements, depletion of hydrogen, and strong stellar winds.
- The surface temperatures of known Wolf–Rayet stars range from 20,000 K to around 210,000 K, hotter than almost all other kinds of stars.
- They were previously called W-type stars referring to their spectral classification.
- Classic (or population I) Wolf–Rayet stars are evolved, massive stars that have completely lost their outer hydrogen and are fusing helium or heavier elements in the core.
- A subset of the population I WR stars show hydrogen lines in their spectra and are known as WNh stars
    - they are young extremely massive stars still fusing hydrogen at the core, with helium and nitrogen exposed at the surface by strong mixing and radiation-driven mass loss.
- A separate group of stars with WR spectra are the central stars of planetary nebulae (CSPNe), post-asymptotic giant branch stars that were similar to the Sun while on the main sequence, but have now ceased fusion and shed their atmospheres to reveal a bare carbon-oxygen core.
- All Wolf–Rayet stars are highly luminous objects due to their high temperatures
- powerful winds emitted by these objects are driven by intense radiation pressure
- Thought to descend from O stars that have lost their hydrogen envelopes to reveal an exposed helium core
- It is estimated that about 50% of Wolf-Rayet stars occur in binary systems. Proposed companions are another Wolf-Rayet star, or a compact companion such as a black hole or neutron star.
- Wolf- Rayet stars are thought to end their lives spectacularly as either a Type Ib or Type Ic supernova explosion.

- Wolf-Rayet galaxies contain mainly Wolf-Rayet stars, which are high-mass post-main-sequence stars that come from the more massive O stars.
- The stars are Population I and contain broad emission lines from dense, high-velocity winds.
- The lines create a bump called the "Wolf-Rayet" bump at 4650-4690 angstroms that allows one to detect them in galaxies.
- nuclear fusion occurs in shells in the stellar core
- amount of energy produced by nuclear fusion in a Wolf-Rayet star is connected to the nebulous area because the higher energy causes high stellar winds that blow off material
- Strong stellar winds would have ionized elements whizzing around in a lot of different directions. These would generate broad emission lines. Strong stellar winds would also drive particles rather far away from the star, which accounts for the large radius the spectrum is observed over.

- First found in Cygnus
- WN- spectrum dominated by nitrogen // WC - spectrum dominated by carbon oxygen
- Divided in subclasses by temperature
- Wolf-Rayet stars would NOT have carbon in photospheres, but carbon stars, Mira Variables, and O-type main sequence stars would have carbon

Active Galaxies:

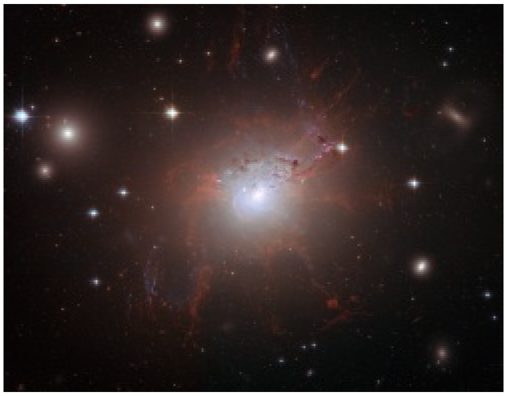
AGN and Quasars:

- AGN, or Active Galactic Nuclei, are defined as galactic nuclei that emit more electromagnetic radiation than a normal galaxy.
- This radiation is emitted in a large jet in one direction.
- In addition, a torus of gas forms around the nucleus perpendicular to the direction of the jet, which can obscure some parts of the galaxy from observers, changing their visual characteristics.
- The six main characteristics that define AGN are: compact angular size, high luminosity, continuum radiation (all types of radiation in the spectrum are emitted), emission lines, variability of emission, and strong radio emission.
    - However, they are the same type of object viewed from different angles
- Quasars, also known as quasi-stellar radio sources or quasi-stellar objects, are the most luminous type of AGN.
    - 
- Active Galaxies are galaxies which contain an AGN at their center.
- Do NOT indicate high planetary formation rates
- Relatively rapid fluctuations (within 1 day) in the electromagnetic output of quasars is an indication of The relatively small size of the emitting regions

Seyfert Galaxies:

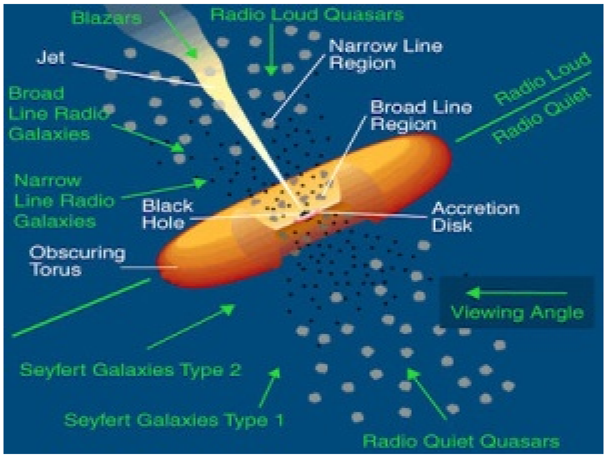
- Seyfert Galaxies are subclasses of active galaxies classified by emission lines of ionized gas.
- The two main classifications are Type 1 and Type 2.

- Type 1 Seyferts emit narrow and broad spectral lines, while Type 2 Seyferts only emit narrow lines.
- Some galaxies can also be classified as numbers between 1 and 2, like 1.5, depending on the relative sizes of the lines.
- Perseus A is an example of a Type 1.5 Seyfert galaxy.



Other classifications:

- AGN and quasars are mainly classified based on the angle that the object is viewed from by an observer on Earth.
- This is because the angle of the electromagnetic radiation emitted from the nucleus can change how visible the object is.
- If the emission jet faces away from the observer, the object will appear less active, and vice versa.
- The diagram at left shows how viewing angle correlates to the type of AGN.
- AGN are classified into two large groups, Radio-Quiet AGN and Radio-Loud AGN.
- In Radio-Quiet AGN, the large jet of radiation faces away from the observer.
- Seyfert galaxies contain Radio-Quiet AGN.
- In contrast, Radio-Loud AGN occurs when the jet of radiation faces the observer, and much more activity is apparent.
- In some cases, the radiation is pointed directly at earth, so an observer can see the radiation jet head-on. → Their objects are known as Blazars.
- BL Lacertae Objects and OVV (optically violent variable) Quasars, which are both very variable (OVV Quasars more so), are both types of Blazars.
- Meanwhile, Radio Galaxies, such as Cygnus A, are galaxies with Radio-Loud AGN which are viewed at a greater angle from the jet.
- Quasars can be Radio-Quiet or Radio-Loud.
- Difference between Quasar and Blazar → quasar is pointed at an angle away from the observer while a blazar is pointed very nearly at the observer



Black Holes:

- Black holes are supermassive objects from which nothing can escape.
- Since light cannot be emitted, they appear as black spots in space.
- They can also alter the appearance of surrounding objects because of the high gravitational pull.
- Stellar-mass black holes have masses at 1.4 to 20 times the Sun.
- They are very dense and result from the collapse of a large star.
- Intermediate-mass black holes are thought to be at the center of globular clusters, and they are larger than stellar-mass black holes.
- The largest black holes, supermassive black holes, are usually the centers of galaxies.
- The center of the Milky Way, Sagittarius A, is thought to be a supermassive black hole.
- AGN are usually supermassive black holes.
- Supermassive black holes can be over one billion solar masses and less dense than water.
- They appear black because their escape velocity is greater than that of the speed of light, and nothing is faster than light.
- If the core ends up with over 2-3 solar masses of matter (because some of the matter in the outer layers fell back onto the core when the star went supernova), even neutron degeneracy pressure can't support the core against its own gravity and it collapses into a black hole
- Once the core contracts to a small enough size, the escape velocity becomes greater than the speed of light! Nothing - not even light - can escape the gravitational pull of the collapsed core
- Because of this, we can't even see the black hole itself; all we can see are its effects on nearby matter
- Black holes are technically only theorized as they can not be directly observed due to the lack of emitted light/radiation (hence the term black hole), but astronomical observations of their possible gravitational effects on nearby systems have led to them being commonly accepted as existing stellar remnants, and products of Type II supernovae

- Many things about black holes are still not completely understood due to their complex nature.
- Uses x ray wavelengths
- No hair theorem: black holes are characterized by only three observable properties: mass, angular momentum and charge
- Intermediate mass Black Holes (IMBHs) in Milky Way would be formed via hierarchical merging in a globular cluster or nuclear star cluster

Schwarzschild Metric:
- describes the spacetime geometry of empty space surrounding any spherical mass.
- In Einstein's theory of general relativity, the Schwarzschild metric (also known as the Schwarzschild solution) is an exact solution to the Einstein field equations that describes the gravitational field outside a spherical mass, on the assumption that the electric charge of the mass, angular momentum of the mass, and universal cosmological constant are all zero. The solution is a useful approximation for describing slowly rotating astronomical objects such as many stars and planets, including Earth and the Sun. It was found by Karl Schwarzschild in 1916.
- Importance → radius below which the gravitational attraction between the particles of a body must cause it to undergo irreversible gravitational collapse. This phenomenon is thought to be the final fate of the more massive stars

Gravitational Waves

Gravitational waves are 'ripples' in space-time caused by some of the most violent and energetic processes in the Universe. The strongest gravitational waves are produced by cataclysmic events such as colliding black holes, supernovae (massive stars exploding at the end of their lifetimes), and colliding neutron stars. Other waves are predicted to be caused by the rotation of neutron stars that are not perfect spheres, and possibly even the remnants of gravitational radiation created by the Big Bang. Thought to be a natural outcome of the theory of relativity

- **Continuous gravitational waves** are thought to be produced by a single spinning massive object like a **neutron star**. Any bumps on or imperfections in the spherical shape of this star will generate gravitational waves as it spins.
- **Compact Binary Inspiral** gravitational waves: all objects LIGO has detected fall into this category. They are produced by orbiting pairs of massive and dense objects like white dwarf stars, black holes, and neutron stars, three types of subclasses: binary neutron star, (BNS) binary black hole (BBH), neutron star black hole binary (NSBH)
- **Stochastic** Signal", so called because the word, 'stochastic' means having a random pattern that may be analyzed statistically but not predicted precisely. These will be the smallest and most difficult gravitational waves to detect, but it is possible that at least part of this stochastic signal may originate from the Big Bang.
- **'burst** gravitational waves' is truly a search for the unexpected—both because LIGO has yet to detect them,

Relativity and Cosmology:

Black Holes:

- One special property of stars is that their entire lives and evolution can mostly be predicted solely from the mass of whatever formed them.
- Stars usually form from large clouds of gas called protostars which collapse from gravitational pressure to form what are known as pre-main-sequence stars.
- As these stars age, their initial mass determines the physics of how the evolve, including how they die.
- If a star has a core that has a mass above the Tolman–Oppenheimer–Volkoff limit, which is debated to be around 2-3 solar masses (i.e. 2-3 times the mass of the sun), it will collapse to form a black hole
- M-sigma relation in astronomy correlates the mass of a galactic central supermassive black hole with the velocity dispersion of the galaxy's bulge

The Big Bang:

- Around 13 billion years ago, the universe began in a blast of energy called the Big Bang.
- The Big Bang started from an infinitesimal point of space and began to expand over time.
- As it cooled, particles began to form and the structure of the Universe began to become more apparent.
- The Big Bang can be divided into 3 main time periods.

Lorentz Transformations:

- According to Einstein's Special Theory of Relativity, an observer moving at a constant velocity will experience events differently than an observer at rest.
- To describe the differences in these observations, the Lorentz transformations can be used to transform values in one reference frame to another.
- The transformations only apply in inertial reference frames, i.e. ones that do not accelerate relative to another inertial reference frame.
- By extension, since rotation requires a change in direction of velocity, which is represented by acceleration, reference frames that are rotating relative to another reference frame are not inertial.

Twin Paradox:

- One paradox involved with time travel is the twin paradox.
- The twin paradox involves two identical twins, one that stays on Earth and one that goes on a rocket that goes at 99% the speed of light.
- When the astronaut goes to a certain distance and comes back, the astronaut finds that the twin on Earth has aged more.
- This is because in the astronaut's frame of reference, time has slowed down, while according to the twin, time has not slowed down.

Gravitational Lensing:

- Einstein's general theory of relativity states that objects with mass cause curvature in spacetime around them, and this effect is the explanation for gravity.

- Used to Study the nature of dark energy and dark matter
- This curvature of spacetime is often thought of using the analogy of a bowling ball on a trampoline pulling down on the fabric, as shown in the figure below.
- This analogy does have downfalls, such as not explaining how the bowling ball weighs down on the trampoline without circling back to gravity, but the idea of curvature is the point here.
- For those who are curious, the curvature is actually caused by complex properties of the energy and momentum of the body of mass, but that is very high-level and not required knowledge for this event.

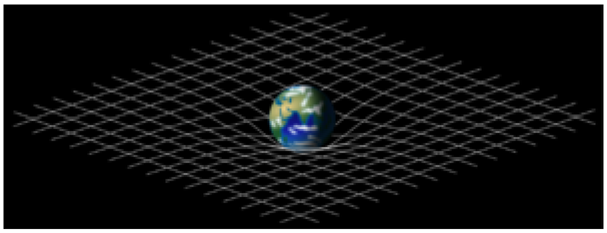
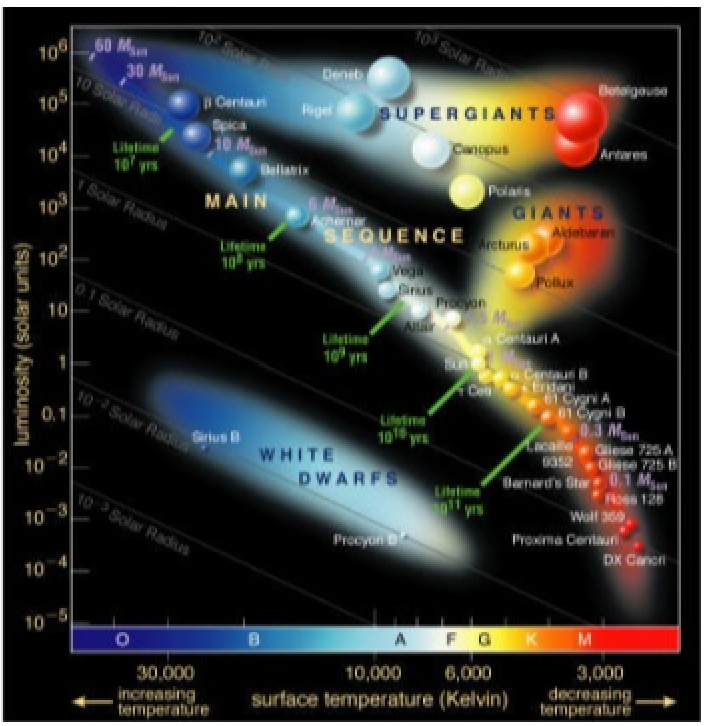
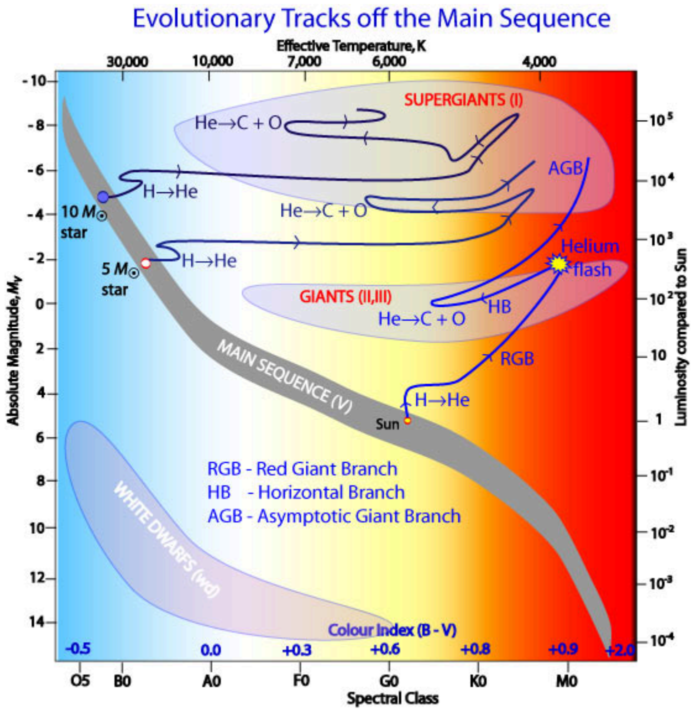


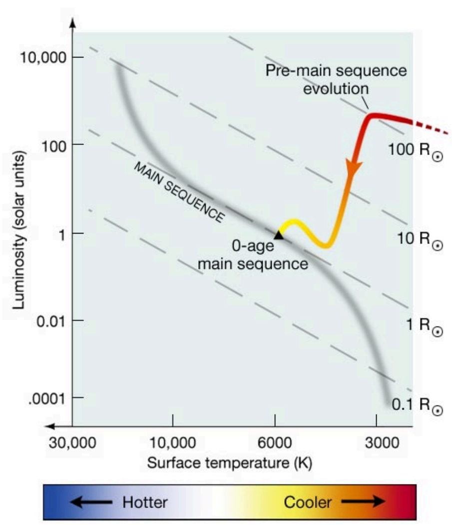
Image depicting curvature of spacetime around the Earth as described by Einstein's general theory of relativity.

- The existence of matter bends space time around the matter, and this spacetime gives a description of how objects move through spacetime.
- All objects in spacetime must follow the curvature of spacetime, and light is no exception.
- Thus, when light approaches near a massive object, it moves along the curvature, causing it to bend at a slight angle known as the angle of deflection.
- This is what makes the light look like it's flowing around the object, creating shapes like an Einstein Ring or an Einstein Cross.
- Since the path of light is altered, near a massive object, the distance the light has to travel to reach the observer also changes.
- However, Einstein showed in his special theory of relativity that the speed of light is constant.
- Since the time it takes an object to travel a distance is dependent on the distance and speed, increasing distance increases the amount of time it takes for the object to travel that distance.
- As a result, gravitational lensing can delay some of the light traveling from a single source, making it appear multiple times in the sky.
- This has been observed many times in the past, proving the existence of gravitational lensing.

Hertzsprung-Russell diagrams:

- plots the temperature of stars against their luminosity (the theoretical HR diagram), or the color of stars (or spectral type) against their absolute magnitude (the observational HR diagram, also known as a color-magnitude diagram).
- The **main sequence** stretching from the upper left (hot, luminous stars) to the bottom right (cool, faint stars) dominates the HR diagram. It is here that stars spend about 90% of their lives burning **hydrogen** into **helium** in their cores. Main sequence stars have a **Morgan-Keenan luminosity class** labeled **V** and a spectral class of (M)
    - Very luminous stars with low temperatures Could have variable diameter depending on spectral class
- The Stefan-Boltzmann relation allows us to draw lines on the Hertzsprung-Russell diagram that are constant radius
- There are more K and M type stars than O and B type stars
- Smallest to largest main-sequence radius (with Morgan-Keenan system): OBAFGKM
- 

- 



- Order of evolutionary stages of star: Red giant branch – main sequence – horizontal branch – asymptotic giant branch
- **red giant** and **supergiant** stars (luminosity classes **I** through **III**) occupy the region above the main sequence. They have low surface temperatures and high **luminosities** which, according to the Stefan-Boltzmann law, means they also have large radii. Stars enter this evolutionary stage once they have exhausted the hydrogen fuel in their cores and have started to burn helium and other heavier elements.
- **white dwarf** stars (luminosity class **D**) are the final evolutionary stage of low to intermediate mass stars, and are found in the bottom left of the HR diagram. These stars are very hot but have low luminosities due to their small size.

1. The **main sequence** stretching from the upper left (hot, luminous stars) to the bottom right (cool, faint stars) dominates the HR diagram. It is here that stars spend about 90% of their lives burning **hydrogen** into **helium** in their cores. Main sequence stars have a **Morgan-Keenan luminosity class** labeled **V**. (hydrostatic equilibrium- is the condition of a fluid or plastic solid at rest, which occurs when external forces, such as gravity, are balanced by a pressure-gradient force.[1] In the planetary physics of Earth, the pressure-gradient force prevents gravity from collapsing the planetary atmosphere into a thin, dense shell, whereas gravity prevents the pressure-gradient force from diffusing the atmosphere into outer space.Hydrostatic equilibrium is the distinguishing criterion between dwarf planets and small solar system bodies)
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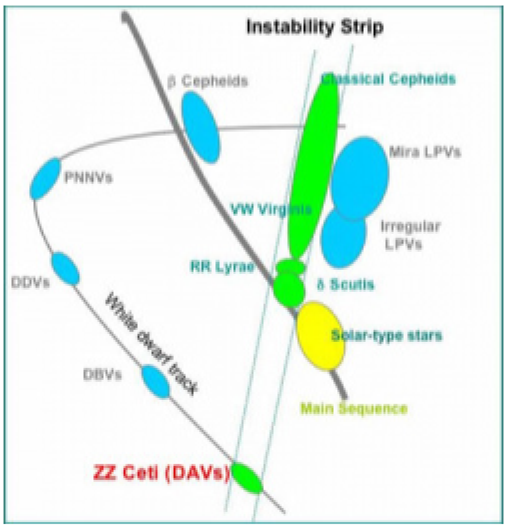
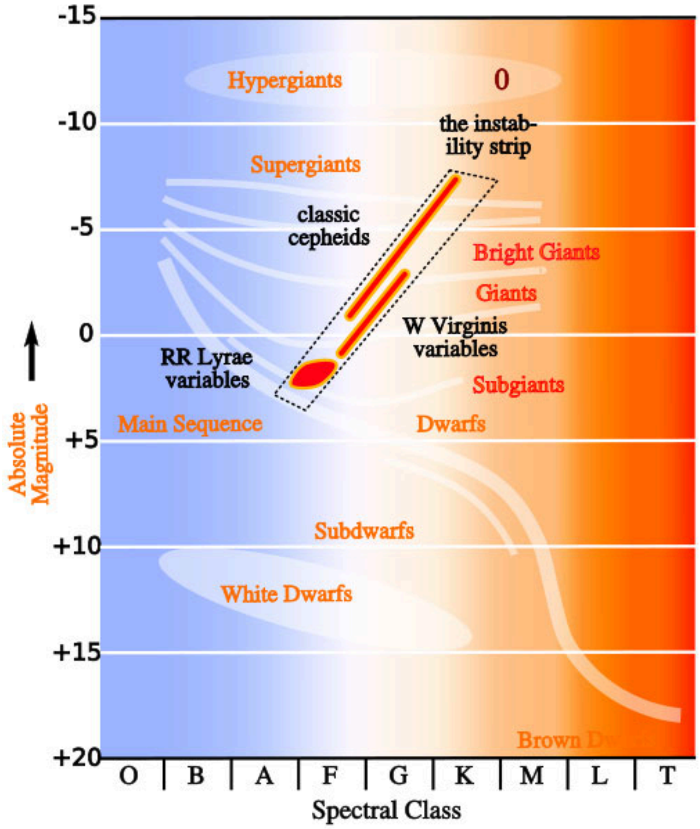
The **Sun** is found on the main sequence with a luminosity of 1 and a temperature of around 5,400 **Kelvin**.

Astronomers generally use the HR diagram to either summarize the evolution of stars, or to investigate the properties of a collection of stars. In particular, by plotting a HR diagram for either a globular or open cluster of stars, astronomers can estimate the age of the cluster from where stars appear to turnoff the main sequence (see the entry on main sequence for how this works).

Instability Strip:

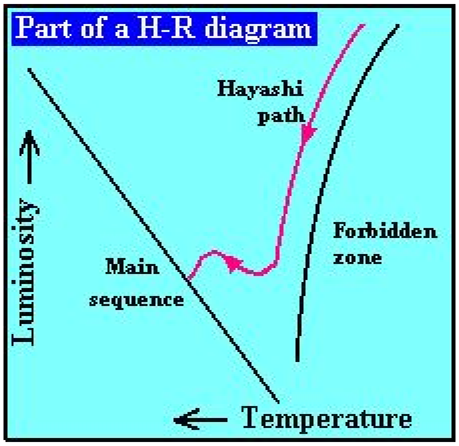
- The Instability Strip is a region on the H-R Diagram in which many variable stars can be found. This strip extends through the A, F, and occasionally G classes above and below the main sequence.
- In this strip, stars have a tendency to be unstable and pulsate, thus causing them to have some variability. Cepheids, RR Lyrae, W Virginis, and ZZ Ceti stars can all be found in this region, as well as other, less common variable stars.

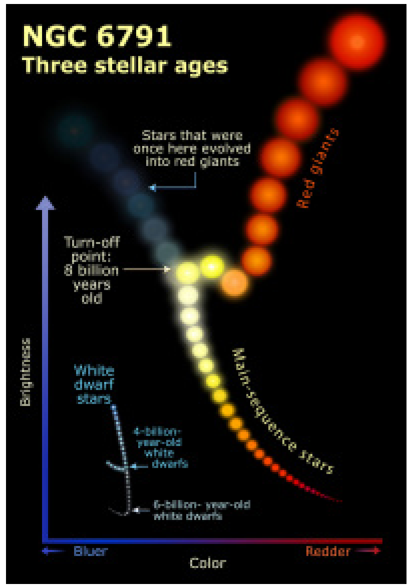




Hayashi Track:

- The Hayashi track explains the lives of low-mass stars with solar masses less than 0.5, and it was developed by Japanese scientist Chushiro Hayashi.
- Protostars (pre main sequence stars) follow this path; luminosity-temperature relationship
- All stars in this track become fully convective, and so it mostly applies to red dwarfs.
- As the stars become denser, they become less luminous, until fusion begins, when they get warmer. This leads them to the main sequence.
- The Hayashi boundary is found at about 4000 K and marks the boundary for which the track can be followed.
- Stars cooler than this temperature will get warmer until they hit the boundary; there, it will stop and remain within this boundary.
- Stars that have solar masses higher than 0.5 will follow the first part of the Hayashi track, but break off midway to follow the Henyey track, so named after American astronomer Louis Henyey.
- In this track, the stars get hotter, and move horizontally until they reach the main sequence. This is characteristic of more Sun-like stars.
- Henyey track → pre-main sequence star = Herbig Ae/Be star
- Hayashi track → pre-main sequence star = T Tauri star (which appears below the main-sequence)





Turnoff Point:

- The point at which the stars deviate from the main sequence after using up most of their fuel is known as the turnoff point.
- The bend in the evolutionary track can be caused by the development of a radiative core/zone
- This is useful as a dating mechanism for globular clusters, since once stars become red giants, their lifespan is practically over on a universal standpoint.
- By mapping the stars in a globular cluster on an H-R diagram, one can clearly see where there is a turnoff from the main sequence, so the approximate age of the cluster is about the same as the age of the stars at the turnoff point.
- Young clusters will have many blue stars, and the turnoff point will be in the O or B classes of the diagram.
- Conversely, older clusters will be made almost entirely of red and yellow stars, and the turnoff point will be much further to the right.
- However, red dwarves do not have a turnoff point, since they do not grow from dwarf status, so clusters with only red dwarves cannot be dated through this method.

Stellar Classification:

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 most mass and M being the coolest and least mass). 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".
- A change in mass can show that a star is changing class when its brightness is increasing

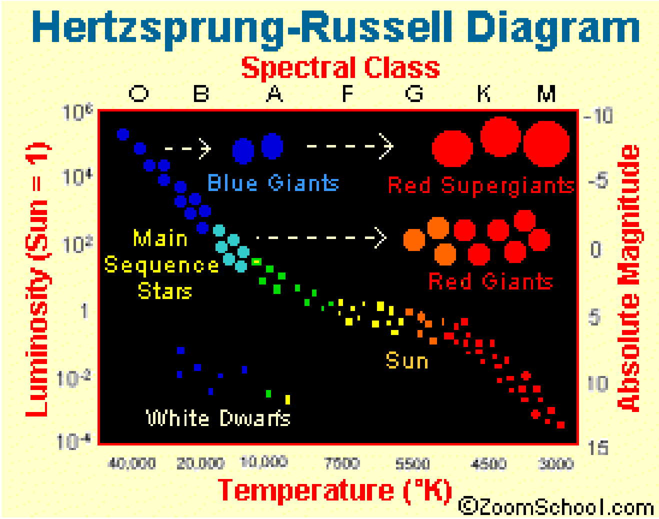
- Of all the stars with mass 1 M(sun), the largest stars tend NOT to be the highest in temperature
- Spectral type A has the strongest lines of neutral hydrogen
- O & B spectral types of stars cause the glow that forms H II regions
- FU Orionis → special type of object F that young stars undergo stages of about 10-20 times before entering the main-sequence
    - Rapid and profound fluctuations in luminosity caused by Abrupt mass transfer from accretion disc onto T-Tauri star & collapse of mass from disk to star surface
- *Type A color is blue/white (idk some test said it was blue)
- If you want to measure a star's hydrogen lines to perform stellar classification, you plot the intensity of light of different wavelengths

Spectral Class Properties

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

Spectral Type	Temperature (Kelvin)	Spectral Lines
O	28,000 - 50,000	Ionized helium
B	10,000 - 28,000	Helium, some hydrogen
A	7500 - 10,000	Strong hydrogen, some ionized metals
F	6000 - 7500	Hydrogen, ionized calcium (labeled H and K on spectra) and iron
G	5000 - 6000	Neutral and ionized metals, especially calcium; strong G band
K	3500 - 5000	Neutral metals, sodium
M	2500 - 3500	Strong titanium oxide, very strong sodium

- Idk columbia test said G type stars like the Sun have strong hydrogen lines



Main Sequence (V)

Spectral Type	Temperature (K)	Absolute Magnitude	Luminosity (in solar luminosities)	Mass (in solar masses)
O5	54,000	-10.0	846,000	30.3
O6	45,000	-8.8	275,000	22.9
O7	43,300	-8.6	220,000	21.7
O8	40,600	-8.2	150,000	19.7
O9	37,800	-7.7	95,000	17.6
B0	29,200	-6.0	20,000	12.0
B1	23,000	-4.4	4600	8.24
B2	21,000	-3.8	2600	7.14
B3	17,600	-2.6	900	5.48
B5	15,200	-1.6	360	4.36
B6	14,300	-1.2	250	3.98
B7	13,500	-0.84	175	3.64
B8	12,300	-0.23	100	3.16
B9	11,400	0.29	62	2.81
A0	9600	1.4	22	2.17
A1	9330	1.6	18	2.06
A2	9040	1.8	15	1.97
A3	8750	2.1	12	1.86
A4	8480	2.3	10	1.78
A5	8310	2.4	9.0	1.73
A7	7920	2.7	6.7	1.61

F0	7350	3.2	4.3	1.44
F2	7050	3.5	3.3	1.35
F3	6850	3.7	2.8	1.29
F5	6700	3.8	2.4	1.25
F6	6550	4.0	2.1	1.20
F7	6400	4.1	1.8	1.16
F8	6300	4.2	1.7	1.14
G0	6050	4.5	1.3	1.07
G1	5930	4.6	1.2	1.04
G2	5800	4.8	1	1.00
G5	5660	4.9	0.86	0.963
G8	5440	5.2	0.68	0.908
K0	5240	5.4	0.54	0.857
K1	5110	5.6	0.46	0.824
K2	4960	5.8	0.38	0.785
K3	4800	6.0	0.31	0.746
K4	4600	6.3	0.24	0.700
K5	4400	6.6	0.19	0.660
K7	4000	7.3	0.10	0.562
M0	3750	7.7	0.069	0.513
M1	3700	7.8	0.064	0.503
M2	3600	7.9	0.054	0.482
M3	3500	8.1	0.046	0.463

M3	3500	8.1	0.046	0.463
M4	3400	8.3	0.038	0.442
M5	3200	8.7	0.026	0.402
M6	3100	8.9	0.022	0.385
M7	2900	9.4	0.014	0.346
M8	2700	9.9	0.0093	0.311
L0	2600	*	0.0074	0.293
L3	2200	*	0.0027	0.227
L8	1500	*	0.00026	0.126
T2	1400	*	0.00017	0.114
T6	1000	*	0.000021	0.0680
T8	800	*	0.0000055	0.0483

*- not visible to the human eye (for the most part)

Giants (III)

Spectral Type	Temperature (K)	Absolute Magnitude	Luminosity (in solar luminosities)
G5	5010	0.7	127
G8	4870	0.6	113
K0	4720	0.5	96
K1	4580	0.4	82
K2	4460	0.2	70
K3	4210	0.1	58

K3	4210	0.1	58
K4	4010	0.0	45
K5	3780	-0.2	32
M0	3660	-0.4	15
M1	3600	-0.5	13
M2	3500	-0.6	11
M3	3300	-0.7	9.5
M4	3100	-0.75	7.4
M5	2950	-0.8	5.1
M6	2800	-0.9	3.3

Supergiants (I)

Spectral Type	Temperature (K)	Absolute Magnitude	Luminosity (in solar luminosities)
B0	21,000	-6.4	320,000
B1	16,000	-6.4	280,000
B2	14,000	-6.4	220,000
B3	12,800	-6.3	180,000
B5	11,500	-6.3	140,000
B6	11,000	-6.3	98,000
B7	10,500	-6.3	82,000
B8	10,000	-6.2	73,000
B9	9700	-6.2	61,000

A0	9400	-6.2	50,600
A1	9100	-6.2	44,000
A2	8900	-6.2	40,000
A5	8300	-6.1	36,000
F0	7500	-6	20,000
F2	7200	-6	18,000
F5	6800	-5.9	16,000
F8	6150	-5.9	12,000
G0	5800	-5.9	9600
G2	5500	-5.8	9500
G5	5100	-5.8	9800
G8	5050	-5.7	11,000
K0	4900	-5.7	12,000
K1	4700	-5.6	13,500
K2	4500	-5.6	15,200
K3	4300	-5.6	17,000
K4	4100	-5.5	18,300
K5	3750	-5.5	20,000
M0	3660	-5.3	50,600
M1	3600	-5.3	52,000
M2	3500	-5.3	53,000
M3	3300	-5.3	54,000
M4	3100	-5.2	56,000
M5	2950	-5.2	58,000

Yerkes Classification:

- Further, stars can be classified into different luminosity classes.
- Decreasing Surface Gravity: VII > VI > V > IV > III > II > I > 0
- VII = Dwarfs (D); VI = subdwarfs (sd)
- In order of Stellar Evolution: V, IV, III, VII

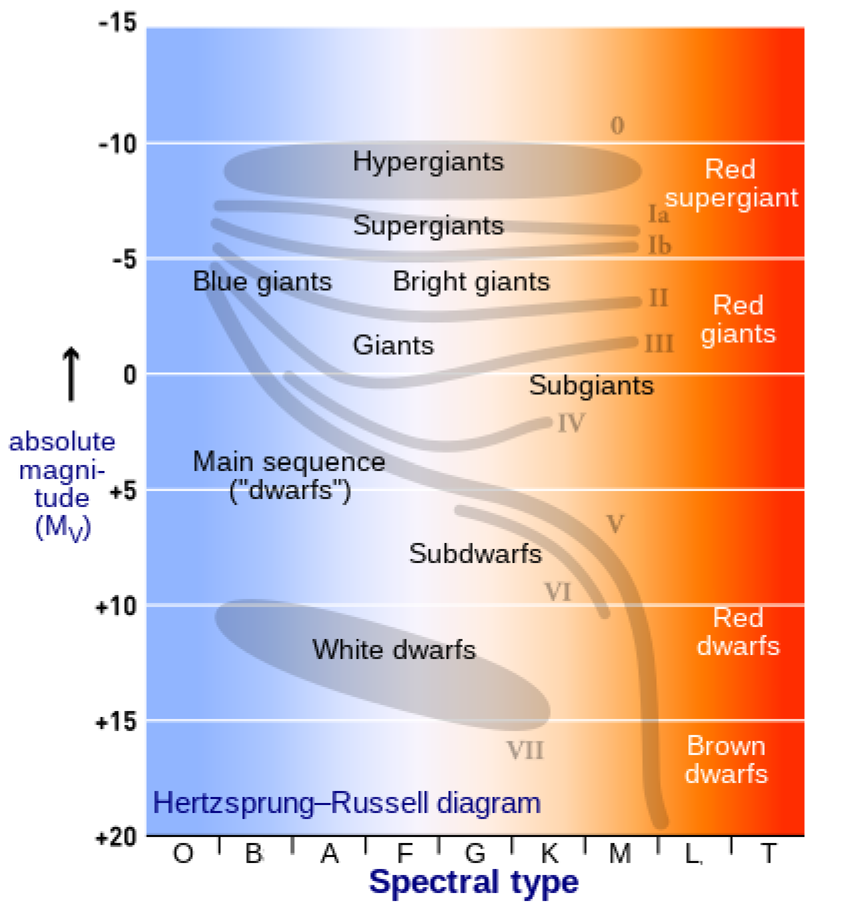
Yerkes Classification

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

Luminosity Class	Description	Comments
0	Hypergiants	extreme
Ia	Supergiants!	large and luminous
Ib	Supergiants!	less luminous than Ia
II	Bright Giants	
III	Giants	
IV	Sub-Giants	
V	Dwarfs	Main Sequence
sd	Sub-Dwarfs	
D	White Dwarfs	

Peculiar Code / Features:

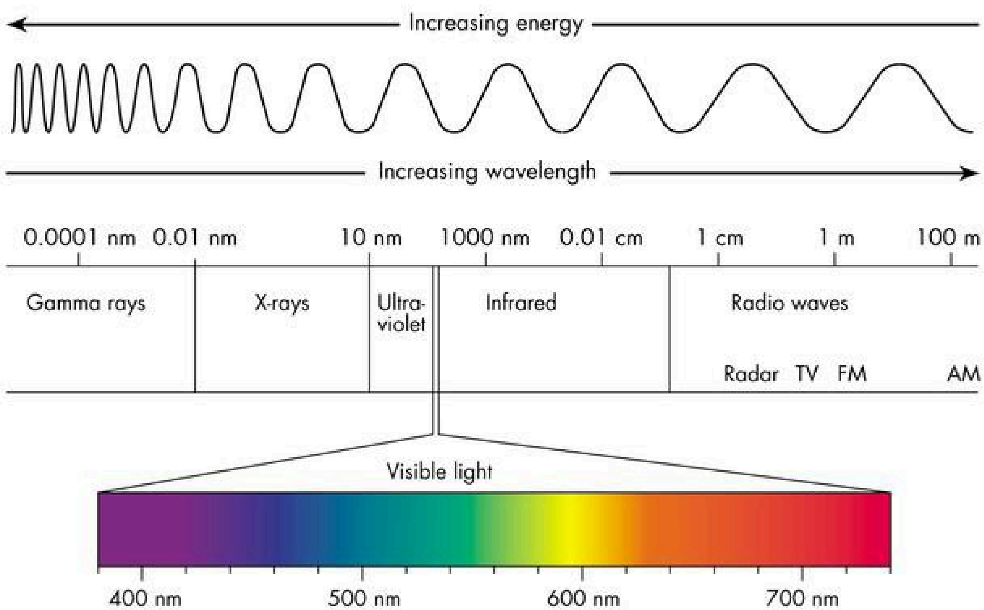
Peculiarity Code	Description
comp	composite spectrum
e	emission lines present
f	NIII and HeII emission (O stars)
m	enhanced metal features
n	broad absorption features
nn	very broad absorption features
neb	nebular features present
p	other peculiarity
s	very narrow absorption lines
sh	shell star
var	variable spectral features
wl	weak features
:	uncertainty



Color Index:

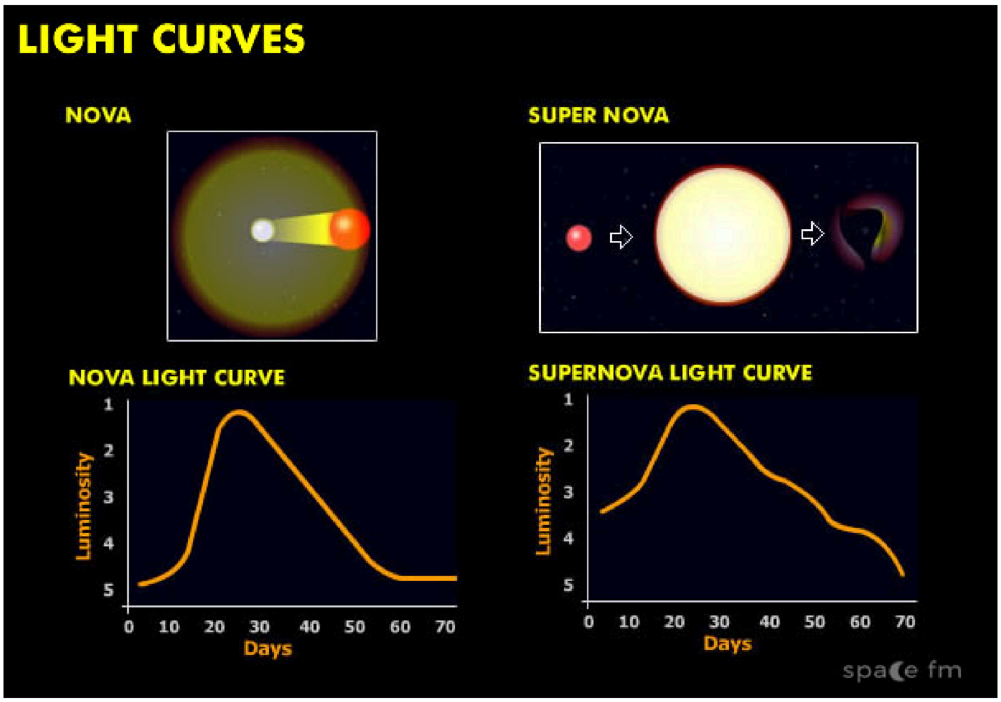
- In astronomy, the **color index** is a simple numerical expression that determines the color of an object, which in the case of a star gives its temperature. The lower the color index, the more blue (or hotter) the object is. Conversely, the larger the color index, the more red (or cooler) the object is.
- Stars of different spectral classes demonstrate different profiles across multiple color indices
-

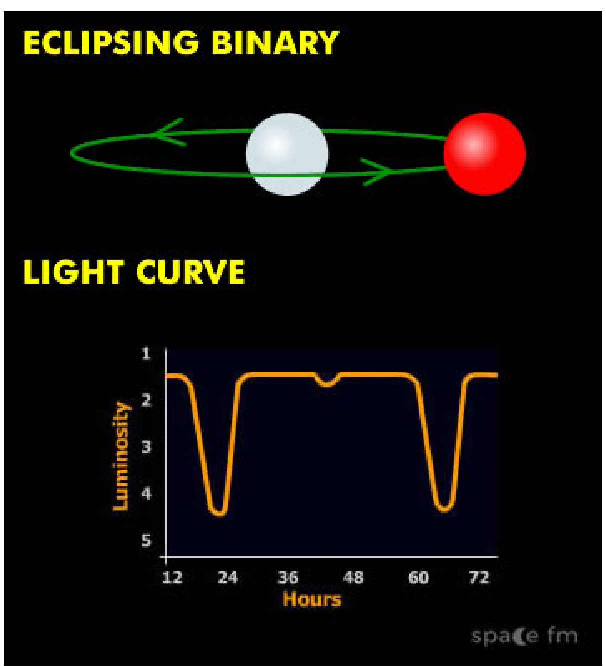
B-V	T_{eff}		B-V	T_{eff}		B-V	T_{eff}		B-V	T_{eff}	
-0.40	113017	#9bb2ff	0.25	7483	#eeefff	0.90	5052	#ffe8ce	1.55	3892	#ffd29c
-0.35	56701	#9eb5ff	0.30	7218	#f3f2ff	0.95	4948	#ffe6ca	1.60	3779	#ffd096
-0.30	33605	#a3b9ff	0.35	6967	#f8f6ff	1.00	4849	#ffe5c6	1.65	3640	#ffcc8f
-0.25	22695	#aabfff	0.40	6728	#fef9ff	1.05	4755	#ffe3c3	1.70	3463	#ffc885
-0.20	16954	#b2c5ff	0.45	6500	#fff9fb	1.10	4664	#ffe2bf	1.75	3234	#ffc178
-0.15	13674	#bbccff	0.50	6285	#fff7f5	1.15	4576	#ffe0bb	1.80	2942	#ffb765
-0.10	11677	#c4d2ff	0.55	6082	#fff5ef	1.20	4489	#ffdfb8	1.85	2579	#ffa94b
-0.05	10395	#ccd8ff	0.60	5895	#fff3ea	1.25	4405	#ffddb4	1.90	2150	#ff9523
-0.00	9531	#d3ddff	0.65	5722	#fff1e5	1.30	4322	#ffdbb0	1.95	1675	#ff7b00
0.05	8917	#dae2ff	0.70	5563	#ffefe0	1.35	4241	#ffdaad	2.00	1195	#ff5200
0.10	8455	#dfe5ff	0.75	5418	#ffeddb	1.40	4159	#ffd8a9			
0.15	8084	#e4e9ff	0.80	5286	#ffebd6	1.45	4076	#ffd6a5			
0.20	7767	#e9ecff	0.85	5164	#ffe9d2	1.50	3989	#ffd5a1			



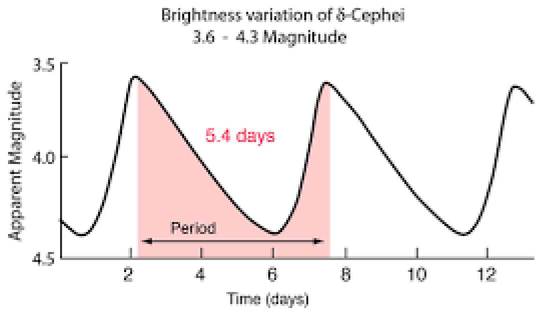
Light curves:

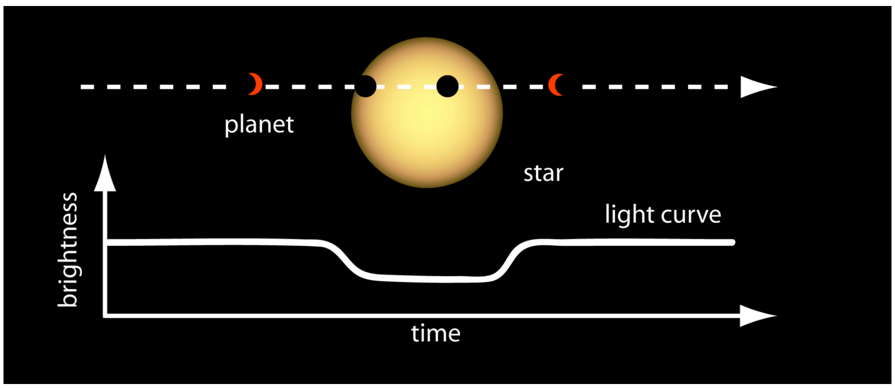
- graphs that show the brightness of an object over a period of time.
- Helps in the study of objects which change their brightness over time, such as novae, supernovae, and variable stars.
- The record of changes in brightness that a light curve provides can help astronomers understand processes at work within the object they are studying and identify specific categories (or classes) of stellar events.
- We know generally what light curves look like for a set of objects, so when we plot a new light curve, we can compare it to those standard light curves to possibly identify the type of object we're observing.
- Peak in light curves (one narrow specific color appears super bright) is called an emission line





Period of a binary star would be difference in time of the two dips (between 24 and 64: 30 hours)





Cosmological distance equations and relationships:

- **Red shift**: The light of objects which are receding from us is shifted to longer wavelengths – towards the red end of the visible spectrum – due to the Doppler Effect. This affects all objects at cosmological distances, which are invariably receding from the Earth due to the continuous expansion of the Universe.

$$z = \frac{\lambda_{obs} - \lambda_{rest}}{\lambda_{rest}}$$

where z = redshift
and λ_{obs} = observed wavelength
and λ_{rest} = rest wavelength
(and λ is the lower case Greek letter lambda)

- **Interstellar reddening: interstellar dust absorbs and scatter more blue light than red light making stars appear redder than they are**
- **Higher reddening→ higher extinction**

- Redshift = low frequencies - stretched out (longer)- occurs when objects move away from us
- Blueshift = high frequencies - compressed waves (shorter)- occurs when objects move towards us

- It's unusual to see carbon in a star's spectrum because the fusion of helium into carbon occurs deep inside stars
- More spectra lines → heavier element because it has more electrons

Einstein's Field Theory:
- relates the geometry of spacetime to the distribution of matter within it
- This leads to the prediction of black holes and models of evolution of the universe

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}$$

where $G_{\mu\nu}$ is the Einstein tensor, $g_{\mu\nu}$ is the metric tensor, $T_{\mu\nu}$ is the stress–energy tensor, Λ is the cosmological constant and κ is the Einstein gravitational constant.

-

The Einstein tensor is defined as

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu},$$

where $R_{\mu\nu}$ is the Ricci curvature tensor, and R is the scalar curvature. This is a symmetric second-degree tensor that depends on only the metric tensor and its first and second derivatives.

The **Einstein gravitational constant** is defined as[6][7]

$$\kappa = \frac{8\pi G}{c^4} \approx 2.07665(5) \times 10^{-43}\ \mathrm{N}^{-1},$$

where G is the Newtonian constant of gravitation and c is the speed of light in vacuum.

The EFE can thus also be written as

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}.$$

In standard units, each term on the left has units of 1/length^2.

General Relativity:
- observed gravitational effect between masses results from their warping of spacetime.
- Provided foundation for current understanding of black holes
- General relativity, also known as the general theory of relativity and Einstein's theory of gravity, is the geometric theory of gravitation published by Albert Einstein in 1915 and is the current description of gravitation in modern physics. General relativity generalizes special relativity and refines Newton's law of universal gravitation, providing a unified

description of gravity as a geometric property of space and time or four-dimensional spacetime. In particular, the curvature of spacetime is directly related to the energy and momentum of whatever matter and radiation are present. The relation is specified by the Einstein field equations, a system of second order partial differential equations.