ASTRONOMY

GENERAL INFORMATION

HERTZSPRUNG-RUSSELL (H-R) DIAGRAMS

-A scatter graph of stars showing the relationship between the stars' absolute magnitude or luminosities versus their spectral types or classifications and effective temperatures.

-Can be used to measure distance to a star cluster by comparing apparent magnitude of stars with abs. magnitudes of stars with known distances (AKA model stars). Observed group plotted and then overlapped via shift in vertical direction. Difference in magnitude bridge equals distance modulus. ← Known as **Spectroscopic Parallax**.

SPECTRA

HARVARD SPECTRAL CLASSIFICATION (1-D)

-Groups stars by surface atmospheric temp. Used in H-R diag. vs. Luminosity/Abs. Mag.

*Class**	*Color Descr.*	*Actual Color*	*Mass ($M_\odot$)*	*Radius($R_\odot$)*	*Lumin.($L_\odot$)*
O	Blue	Blue	≥ 16	≥ 6.6	≥ 30,000
B	Blue-white	Deep B-W	2.1-16	1.8-6.6	25-30,000
A	White	Blue-white	1.4-2.1	1.4-1.8	5-25
F	Yellow-white	White	1.04-1.4	1.15-1.4	1.5-5
G	Yellow	Yellowish-W	0.8-1.04	0.96-1.15	0.6-1.5
K	Orange	Pale Y-O	0.45-0.8	0.7-0.96	0.08-0.6
M	Red	Lt. Orange-Red	0.08-0.45	≤ 0.7	≤ 0.08

* *Very weak stars of classes L, T, and Y are not included.*

-Classes are further divided by Arabic numerals (0-9), and then even further by half subtypes. The lower the number, the hotter (e.g. A0 is hotter than an A7 star)

YERKES/MK SPECTRAL CLASSIFICATION (2-D!)

-Groups stars based on both temperature and luminosity based on spectral lines.

LUMINOSITY CLASSES (Also uses "OBAFGKM")

O – hypergiants
I – supergiants
II – bright giants
III – normal giants
IV – subgiants
V – M.S. (dwarfs)
VI – subdwarfs
VII –white dwarfs

^ Each classification is further divided into **a**, **ab**, and **b** types, representing *luminous*, *intermediate luminous*, and *less luminous*, respectively. Supergiants also have **Ia-O**, which stands for either "extremely luminous supergiant" or "hypergiant." "M.S." = main sequence. Subdwarves classified further by **sd** and **esd** (subdwarf or extreme subdwarf), while VII class are uncommon and have prescripts of either **wD** or **WD**.

ASTRONOMY

YERKES/MK SPECTRAL CLASSIFICATION (CONTINUED)

-Marginal symbols are used to further distinguish stars:

Symbol	*Example*	*Explanation*
-	G2 I-II	Between supergiant and bright giant
+	O9.5 Ia+	Hypergiant (one step up)
/	F2 IV/V	Either subgiant or dwarf

SPECTRA IN-DEPTH (MAIN SEQUENCE)

O	- Main-sequence (hydrogen-burning core) star, spectral type O and luminosity class V - Very rare, very massive, with extremely short lifespans (first to leave main seq.) - 0.00003% of local stars are of spectral type O. - Most output is in the ultraviolet range
B	- Main-sequence star, spectral class B, luminosity class V - Extremely luminous, short lifespans, rarely found far from area of formation - ~0.125% of stars in solar neighborhood (M-S) are of spectral class B. - Natural helium spectra with moderate hydrogen lines
A	- Main-sequence star, spectral type A, luminosity class V - More common naked-eye stars with higher tendency to have massive planets - 0.625% of stars in solar neighborhood belong to class A. - Strong hydrogen lines with strengthening Ca II lines
F	- Main-sequence star, spectral type F, luminosity class V - Technically a "dwarf star," so may be referred to as a yellow-white dwarf. - ~3.03% of stars in the solar neighborhood are class F stars. - Weaker hydrogen lines and strengthening lines of Ca II
G	- Main-sequence star of spectral type G, luminosity class V - Lifetime of ~10bn years until Hydrogen fusion ceases and transitions to a red giant - ~7.5% of local stars are of class G, the most well-known being the Sun, of class G2V - Yellow supergiants are extremely rare; most supergiants are between O-B or K-M
K	- Main-sequence star of spectral type K, luminosity class V - Due to low mass and intermediate size, have longer lifespans (15-30bn years) - ~12% of main-sequence stars in the solar neighborhood belong to class K - AKA "orange dwarves" with mostly neutral metals lines and weak hydrogen lines
M	- Very low-mass, main-sequence stars of spectral type M, luminosity class V - Due to low mass and low surface temperature, red dwarves are very dim stars - ~76% of local main-sequence stars are class M stars, making them very common - Have incredibly long lifespans due to lack of buildup at core, lifespans of 10tn+ years

ASTRONOMY

STELLAR "CHEMISTRY"

-Stars are composed, by mass, mainly of hydrogen and helium. Our sun is roughly 71% hydrogen (H) and 27% helium (He), with the remainder being various heavier elements. Iron (Fe) is typically used as a measure for the heavier elements as it is relatively common and its absorption lines are easy to measure.

-The presence of certain elements in stars can be determined via interpretation of the star's absorption lines in its emission spectrum. In general, "metals" are non H and He.

-The amount of metal present in a star gives hint to its age. Stars can go into three groups:

Population	*Characteristics*
I	Population I stars have high percentages of metals. The youngest stars belong to this group, and are more likely to have planets, as the accretion of heavier elements is thought to be key in the formation of planets. They are more common in the arms of the galaxy.
II	Population II stars have relatively little metal. They are older and are believed to have created the other elements in the Periodic Table, with exception to the more unstable ones. Usually found in globular clusters and the galactic bulge and galactic halo.
III	A theoretical class of stars with practically no metal content with the exception of elements created in the Big Bang.

-Each stellar class also differs in its absorption and emission lines:

Class	*Characteristics*
O	Dominant He II absorption (and sometimes emission) lines and prominent ionized (Si IV, O III, N III, C III) and neutral helium lines which strengthen from O5-O9 with prominent hydrogen Balmer lines
B	Neutral helium lines, most prominent at the B2 subclass, with moderate hydrogen lines. Balmer series hydrogen lines grow stronger through the B class. Ionized metals include Si II and Mg II
A	Balmer series lines peak, with strong hydrogen lines. Also present are lines of ionized metals, including Fe II, Mg II, and Si II, which are at a maximum at A5. Ca II lines strengthen at this point.
F	Strengthening *H* and *K* lines of Ca II. Neutral metals Fe I and Cr I make gains on ionized metals by late F. Weaker hydrogen lines and ionized metals characterize the class.
G	Very prominent *H* and *K* lines of Ca II, peaking at G2. Have weaker hydrogen lines than F. Along with ionized metals, neutral metals lines are present in the spectra.
K	Extremely weak, sometimes nonexistent, hydrogen lines. Mostly neutral metals (Mn I, Fe I, Si II).

M	TiO lines show in addition to lines for other oxide molecules, in hthe visible and all neutral metals. Hydrogen lines are usually absent. Vanadium Oxide appears by late M.

MAGNITUDES AND LUMINOSITY

-**Magnitude** is the logarithmic measure of the brightness of an object. The two specific types distinguished by astronomers are *apparent magnitude* and *absolute magnitude*.

-**Apparent magnitude (m)** is the measure of the brightness of a celestial object, as seen from Earth. The lower the value, the brighter the object. The visual spectrum is usually used as the basis for apparent magnitude, although the near-infrared may also be used. A light curve may be used to plot an object's apparent magnitude versus time.

-**Absolute magnitude (M)** is the measure of the brightness of a celestial object at a distance of 10 parsecs away from the viewer. Absolute magnitude uses the same conventions as visual magnitude, so a change in 5 magnitudes corresponds to a factor of 100 times (e.g. object with mag. -16 is 100x brighter than object with mag. -11). Absolute magnitude can be related to apparent mag. and distance using the **distance modulus,** where m is apparent mag. and d is distance in parsecs:

$$m - M = 5\log(d) - 5$$

-**Luminosity** can be interpreted as a measure of a brightness. In astronomy, it is used to measure the total amount of energy emitted by a star or other celestial object per unit time. This can be expressed in SI units of joules per second or watts. The symbol $L_\odot$ is used to represent the luminosity of the Sun, equal to 3.846×10^{26} W.

LIGHT CURVES

-Light curves are the results of timing experiments that track the change in an object's intensity over time. Information shown in a plot of relative brightness versus time.

-Can be periodic, like those of Cepheid variables and other periodic variables, or aperiodic like those of novae, supernovae, and cataclysmic variable stars like dwarf novae.

-Light used to produce curve usually belongs to a certain frequency interval or band.

-Can be used to measure mass of a star by observing binary systems, requiring knowledge of both orbital pd. and avg. orbital distance using Newton's version of Kepler's Third Law.

-Can also be used to distinguish supernovae types (due to various differences)

-By using the *Period-Luminosity relationship*, one can determine the average absolute magnitude of certain variable stars and use it to find distance via the Distance Modulus. (Light curve gives information to solve for average apparent magnitude).

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.

-Pulsating Variable Stars are stars whose atmospheres expand and contract periodically.

-**Cepheid variables** have high luminosities and short periods, with their pulsation periods closely related to their luminosities. Cepheids are used as standard candles to establish distances. They inhabit the upper portion of the instability strip on HR diagram. They are based off of the star Delta Cephei. There are two classes of Cepheids: Classical and Type II.

-**Mira variables** are red giant stars in the very late stages of stellar evolution. 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.

-**RR Lyrae variables** are older, relatively low-mass, metal poor stars with typical pulsation periods of less than one day, possibly as short as seven hours. 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.

-**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. 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.

-**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.

STELLAR EVOLUTION

THE BIRTH OF A STAR

THE STELLAR NURSERY

-Starbirth is relatively common, and occurs in certain patches of **interstellar medium**, the patches of gas and dust between stars in a galaxy. The composition of such medium is about the same as that of stars: 71% hydrogen, 27% helium, and 2% heavier elements.

-Temperature and density varies despite chemical composition consistency.

-Star-forming clouds tend to be especially cold and dense, at around 10-30 Kelvin with a density of about 300 molecules per cubic centimeter (dense for clouds of gas and dust). These types of clouds are referred to as **molecular clouds**, and also include 120+ other kinds of molecules including CO, H_2O, NH_3 (ammonia), and C_2H_5OH (ethyl alcohol).

-Majority of atoms heavier than H and He found in **interstellar dust**. These bits absorb almost all visible light and causes fringe stars to appear redder (by blocking photons). They do not shift spectral lines.

-Clouds glow due to radiation from the infrared and microwave spectrums.

BEGINNING THE PROCESS

-Process starts when gravity causes a cloud to contract (breaking **hydrostatic equilibrium**)

-Gravity overcomes gas pressure, the balance of which normally keeps a cloud stable. Gravity has an advantage at high densities and low temperatures (for temperatures, it is due to lower temperatures resulting in lower gas/thermal pressures).

-Degeneracy pressure also exists in addition to temperature-dependent gas pressure as resistive forces against collapse along with magnetic forces..

-Some sort of external force (e.g. shockwave) can also disrupt equilibrium and trigger a gravitational collapse.

-Gravity obeys the inverse-square law – as the cloud continues to condense and break up, gravity grows stronger in each individual clump.

-Clouds clump up and break apart due to less mass needed for gravity to maintain an advantage over gas pressures and other resistive forces.

-Smaller, denser clouds may continue to collapse, heating up within due to the inability to effectively disperse thermal energy. Thermal energy comes from the release of gravitational potential energy.

THE PROTOSTAR

-Thermal energy will continue to grow as the cloud collapses. Inner gas eventually loses the ability to radiate heat gained by the release of gravitational potential energy (GPE).

-As the cloud collapses, density increases, causing less and less gas to break off (densities high enough that the cloud becomes thermally opaque). Now a **Class O Protostar**.

-At a density of around 10^{-13} grams per cubic centimeter, the center of the cloud becomes optically opaque. When collapse is essentially halted, a core region called the *First Hydrostatic Core* forms. Meanwhile, gas falling inwards collides with this region, creating more heat to heat the core via shock waves.

-At core temp. 2000K, dissociation of H_2 molecules begins along with ionization of H and He atoms. Energy of contraction is absorbed, allowing further contraction.

-Density of infalling material declines to ~10^{-8}g per cubic centimeter, becoming transparent enough to allow for heat to escape. Combined with convection in the interior, radiation of heat allows protostar to continue to contract.

-Due to rising temperatures, gas in the interior will be able to exert enough pressure to counteract forces of gravity, preventing further collapse. Reaches hydrostatic equilibrium.

-Accretion of material into the star is almost complete, object is a **protostar**.

-Accretion of material continues, albeit more slowly, from the circumstellar disk.

-At high enough densities and temperatures, deuterium fusion begins with outward pressure slowing down collapse.

-When accretion stops and surrounding material disperses, object has become a **pre-main sequence star**.

T TAURI AND PRE-MAIN SEQUENCE STARS

-PMS stars' energy comes from gravitational contraction rather than hydrogen fusion

-< $3M_\odot$ stars follow the **Hayashi track**, becoming T Tauri stars and gradually become less and less luminous. Track begins at a temperature of around 4000K.

-**T Tauri stars** fall almost vertically on the HR diagram, becoming less luminous without decreasing much in surface temperature. The star will continue to contract. Contraction continues until stars with <$0.5M_\odot$ develop a radiative zone. Stars of larger mass follow the **Henyey track**, involving increasing temperatures and luminosities until H fusion can begin. They have high lithium abundances, strong stellar winds, and strong spectral lines..

THE MAIN SEQUENCE

PHYSICS

-In the main sequence, stars are in equilibrium due to the outward pressure generated by hydrogen fusion counteracting the force of gravity. They are in hydrostatic equilibrium.

-When star leaves the main sequence depends on its spectral type and mass.

- >2 solar mass stars undergo convection in core regions to stir up recently-produced hydrogen. Below this mass, stars have entirely radiative cores with convective areas near the surface. Stars of smaller mass (< 0.4 solar masses) are fully convective. Convection zones grow with decreasing stellar mass.

-Upper limit for a main-sequence star is 120-200 solar masses. The outward radiation of energy overcomes the gravitational attraction and the star cannot hold itself together.

-Lower limit is ~0.08 solar masses. P-P chain cannot occur below this, and “stars” below the limit cannot sustain hydrogen fusion and are referred to as “brown dwarfs.”

“CHEMISTRY”

-At 10m kelvin, stars will begin **hydrogen fusion** via the **proton-proton chain** reaction. Hydrogen is fused first into deuterium and then to helium. P-P chain is primarily found in the lower main sequence.

-Stars with masses slightly over 1 solar mass (~>1.5) will generate a large portion of their energy via the Carbon-Nitrogen-Oxygen cycle, or the **CNO cycle**, for short. This is due to their ability to sustain higher temperatures.

-At 18 million kelvin (T of a star with 1.5+ solar masses) the CNO cycle and PP chains are equally efficient and therefore produce half of a star’s net luminosity each. At 1 solar mass (e.g. the Sun), 1.5% of all energy produced is from the CNO cycle. At 1.8+ solar masses, almost all energy is produced via the CNO cycle.

MATURITY – LEAVING THE MAIN SEQUENCE

-In general, the lower the mass, the longer the lifespan of the star. The mass of a star also determines what happens when it exhausts its supply of hydrogen. When the hydrogen supply is depleted, the outward pressure generated by hydrogen fusion is no longer sufficient to counteract the force of gravity, causing the star to contract.

LOW-MASS STARS

-Stars of <0.23 solar masses become white dwarfs directly after exhausting their fuel sources. This is due to them being fully convective and never developing a degenerate helium core with hydrogen burning shells.

-Slightly more massive stars can become red giants, but never fully develop the ability to properly fuse helium due to low temperatures. They move directly off of the red giant branch and become asymptotic giants with lower luminosities.

-Stars above 0.5 solar mass will reach temperatures necessary for helium fusion and will proceed along as if they were medium-mass stars.

-EOL behaviors of low-mass stars are not properly known due to their longevity.

MEDIUM-MASS STARS

-Stars of roughly 0.5-10 solar masses become **red giants**, which are large, non-main-sequence stars of class K or M. They have high luminosities and are notably, red.

-Red Giants have inert cores with hydrogen-burning shells fusing hydrogen into helium. Accelerated fusion in H burning shell directly above core causes star to expand, causing outer layers of the star to cool and adopt the red color.

-The **red-giant-branch** follows the main-sequence. Here, the core is comprised of helium. The initial contraction of the star is halted by **electron degeneracy pressure**. The gravitational energy released during contraction maintains the fusion of hydrogen outside of the core. Core's gravity accelerates burning of hydrogen and causes the star's luminosity to rise significantly.

-Helium from accelerated H fusion is absorbed by the core, causing it to contract further, further accelerating H fusion. Temperature rises to the point where helium fusion begins via the **triple-alpha process** (@ ~ 1.0×10^8 K core T). He fusion causes the core to expand, causing the star to expand. The end results depend on the star's mass and other features.

-The **asymptotic giant-branch phase** begins when the He in the core has been exhausted, leaving a hot core of carbon and oxygen. He fusion continues in the outer layers. **Mira variables** belong to this branch.

MASSIVE STARS

-Helium ignition may occur before electron degeneracy pressure can become prevalent. This results in the unlikelihood that they survive as red supergiants. Their lives will end in a Type II supernova.

-Extremely massive stars will rapidly expel their own envelopes, allowing them to retain very high surface temperatures and, along with them, their blue-white color.

-Stars with heavier cores will continue to heat up until neon decays into oxygen and helium. Temperatures rise, triggering the fusion and formation of other elements. Eventually, temperatures will rise until most nuclei can be partially broken down.

-**Red supergiants** are formed following the fusion of all hydrogen in the core of a supermassive star (usually around 10 solar masses). Their helium-burning phase is spent as red supergiants. They display variability and are extraordinarily bright and large.

DEATH OF A STAR

COLLAPSE!

-A massive, evolved star will finally collapse when nucleosynthesis reaches Iron-56. The fusion process expends more energy than it produces. If the mass of the core exceeds 1.44 solar masses (the **Chandrasekhar limit**), the core will undergo a sudden, catastrophic collapse into either a neutron star or a black hole, depending on mass lost and whether or not certain limits are reached.

SUPERNOVAE

-The catastrophic and very violent death of a high-mass star (with a core mass exceeding 1.44 solar masses). Energy transferred from core collapse to rebounding material is enough to accelerate material to beyond escape velocity. Alternatively, the reignition of nuclear fusion in a degenerate star may cause a supernova. In any case, star goes boom!

TYPE I SUPERNOVAE

-**Type I supernovae** are distinguished from Type II supernovae by the lack of hydrogen lines, or **Balmer lines**, in the emission spectra. The presence of other lines in the spectra further divides the type.

-**Type Ia supernovae** occur in binary systems where one star is a white dwarf and the other is a star that can be of giant mass to an even smaller white dwarf. Normally restricted to less than 1.38 solar masses (the Chandrasekhar mass), should a white dwarf of oxygen-carbon variety exceed it, nuclear fusion may start up again. The mass is obtained by the accretion of material from its binary companion. If accretion continues for a long enough period of time (and a nova or dwarf nova does not occur), the star will approach the Chandrasekhar limit. However, ~1% from the limit, rising temperatures

powered by carbon fusion heats the core up. Degeneracy pressure's independence from temperature means that it is unable to scale to the rise in pressure to keep the star stable. The uncontrolled nuclear reaction that follows releases enough energy to unbind the star from the forces that hold it together. Alternatively, two white dwarfs can merge.

-Because white dwarfs are relatively consistent in terms of composition, size, and mass, Type Ia supernovae are used as alternatives to Cepheids and other standard candles to measure cosmological distances.

-**Type Ib and c supernovae** are similar in mechanics to Type II supernovae, although, like Type Ia supernovae, they lack hydrogen lines. They occur due to the core collapse of a supermassive star. The collapse of the star's core expels the outer layers. Type Ib and Ic supernovae are thought to have already lost their outer hydrogen shells and much of their helium shells. Type Ic supernovae happen to lack the 587.6nm helium lines as compared to Type Ib. Both show Ca, O, and Mg lines as they age, while Type Ia supernovae are eventually dominated by Fe lines.

TYPE II SUPERNOVAE

-A **Type II supernova** occurs when the inert core of a supermassive star reaches a mass beyond 1.44 solar masses. Electron degeneracy pressure can no longer counter gravity, resulting in a cataclysmic implosion that expels the outer layers of the star. Reversed beta-decay from the overcoming of electron degeneracy results in the formation of neutrons and neutrinos. It also creates a devastating shockwave that can disrupt molecular clouds and other systems.

-Core collapse in a large star occurs in steps, where collapse leads to increased pressures and temperatures required to fuse a heavier element. This continues until Fe-56. Collapse is eventually halted by strong forces and neutron degeneracy pressure.

-The light curves of Type II supernovae normally display Balmer hydrogen absorption lines. **Type IIP** supernovae have a distinctive "flat" section in their light curves, while **Type IIL** supernovae show a steady decline in brightness following its peak. The result may be either a **black hole** or **neutron star**, depending on certain conditions.

-The light curves of Type II supernovae are generally “longer” than those of Type I supernovae – that is, the duration of the supernova is longer and the decline in brightness is flatter. Type I supernovae are also usually brighter, but the dropoff is quicker.

REAMNANTS

WHITE DWARFS

-The remnant of a star of less than 8 solar masses. Formed when the outer layers of a red-giant class star are expelled due to instability as a result of the helium fusion process. Pulsations build up to the point where the outer layers of the star are expelled. The result at the center is a degenerate carbon-oxygen core, supported only by electron degen. press.

-White dwarfs are extremely hot (~100000K surface temp. at formation), yet do not release energy as a result of nuclear fusion reactions. Because the star no longer undergoes fusion, it gradually cools off over the years, becoming a black dwarf at the end. They are incredibly dense and compact, with a maximum mass being around 1.38 solar masses.

-It is possible for a white dwarf to undergo nuclear fusion again via the accretion of material from a binary partner. The result may be either dwarf novae, novae, or a Type Ia supernova, depending on how much mass is accumulated and how the extra mass works.

NEUTRON STARS

-The result of the core collapse of a supermassive star with a mass above 8 solar masses.

-Formed via reverse beta-decay when electron degeneracy pressure is overcome when the mass of the core exceeds 1.44 solar masses. They resist further compression with neutron/quantum degeneracy pressure and the Pauli Exclusion Principle, similar to, yet stronger than, electron degen.

-Are the smallest and densest stars known, with incredibly powerful magnetic fields.

-Conservation of momentum following collapse of a supergiant star ensures that the neutron star will rotate extremely rapidly, slowly slowing down over time.

PULSARS

-Highly magnetized, rotating **neutron stars** emitting beams of electromagnetic radiation. Name comes from the way of detecting the beams: when the beam periodically hits Earth due to the star's rotation.

-Short, regular rotational periods make pulsars useful for timekeeping and scientific studies. Due to the massive shrinkage in radius, the speed of rotation is extremely quick. Because of its (comparatively) low moment of inertia, it slows down very slowly over time.

-Radiation if projected from pulsars' magnetic poles. The power of a pulsar may come from its rotation, accretion of material (accounting for most X-ray pulsars), or magnets.

MAGNETARS

-Neutron stars with extremely powerful magnetic fields. Decay of the field powers the emission of strong beams of high-energy electromagnetic radiation, including X-rays and gamma rays.

-Comparatively slow in rotation compared to other kinds of neutron stars.

BLACK HOLES

-**Stellar mass black holes** are remnants of the gravitational collapse of a supermassive star. AKA collapsars. They have masses ranging from 3-10s of solar masses, and are formed when the **Tolman-Oppenheimer-Volkoff limit** is reached (>3-4 solar masses).

-At the point where a black hole forms, not even neutron degeneracy pressure can withstand the force of gravity. The formation of a black hole is nearly guaranteed.

-An important part of X-ray binaries. Light cannot escape the gravity of a black hole.

NEBULAE

-**Planetary nebulae** are the ionized discharged gas layers of a star. At the centers are often white dwarfs as a result of the death of mid-sized stars whose cores failed to exceed the Chandrasekhar limit. They are usually about 1 light-year across and get their color from ionized particles.

-Other nebulae like the Crab Nebula, M1, are remnants of supernovae explosions where stellar material is violently expelled due to the collapse of a star.

X-RAY BINARIES

-**X-ray binaries** are a class of binary stars luminous in X-rays. One member is the *donor* (usually a star) while the other is an *accretor*, usually a compact object like a white dwarf, neutron star, or black hole.

-The infall of matter releases gravitational potential energy in the form of X-rays.

WHAT ABOUT VARIABLE STARS?

CEPHEID VARIABLES

-**Classical Cepheids** belong to a class of unstable yellow supergiants of spectral classes F6-K2. They are 4-20 times more massive than the Sun and may be up to 100,000 times more luminous.

-**Type II Cepheids** belong to spectral classes F6-K2. They are typically older, metal-poor stars. They belong to the Population II subclass of stars in terms of metal content.

RR LYRAE VARIABLES

-A class of periodic variable stars commonly found in globular clusters. They are pulsating horizontal branch stars of spectral class A and sometimes F. They are relatively old, metal-poor Population II stars.

-**RRab** variables are the majority type which display steep rises in brightness of about 91%, **RRc** have shorter periods and var. of about 9%, and **RRd** are rare, double-mode pulsators.

S DORADUS VARIABLES

-AKA **Luminous Blue Variables**, S Doradus variables are unstable supergiant or hypergiant stars. They have very high masses and are B-type stars with lifetimes as short as a few million years. Because of this, they are very rare. Several supernovae have been associated with LBVs.

MIRA VARIABLES

-Characterized by very red colors and long pulsation periods, Mira variables are late-stage red giants in the asymptotic giant branch. They are old and will become white dwarfs and planetary nebulae in a few million years.

-Have masses of less than $2M_\odot$ and have already undergone helium fusion in their cores.

SEMIREGULAR VARIABLES

-Giants or supergiants of intermediate and late spectral type with periods ranging from 20-2000 days. Light curve shapes may be variable each time.

-**SRA** Spectral-type (M, C, S / Me, Ce, Se) giants with persistent periodicity and usually small amplitude. Amplitudes and light curves generally vary. Essentially Mira variables pulsating in an overtone.

-**SRB** Spectral type (M, C, S / Me, Ce, Se) giants with poorly defined periodicity (irregular). May sometimes cease to vary at all for some time. 2+ simultaneous periods of variation.

-**SRC** Spectral type (M, C, S / Me, Ce, Se) supergiants with amplitudes of about 1 mag and periods of light variation from 30 to several thousand days.

-**SRD** Giants and supergiants of F, G, or K spectral types, sometimes with emission lines in spectra. 0.1-4 mag var. in light, per. 30-1100 days.

DWARF/RECURRENT NOVAE

-**Dwarf nova**: periodic outbursts when a white dwarf accretes matter which collapses onto the dwarf, releasing much energy without destroying the star.

-**Recurrent novae**: novae occurring over and over again. Bimodal mag. Light curves. Ejected matter can be detected spectroscopically which is the difference between dwarf nova.

ORBITAL MOTIONS, DISTANCES, AND MATHEMATICS

KEPLER'S LAWS

KEPLER'S FIRST LAW – LAW OF ELLIPTIC ORBITS

-Each star (or planet) moves in an elliptical orbit with the center of mass at one focus.

KEPLER'S SECOND LAW – LAW OF EQUAL AREAS

-A line between one star and the other (radius vect.) sweeps out equal areas in equal times.

KEPLER'S THIRD LAW – LAW OF HARMONICS

-The square of a star's orbital period is proportional to its mean distance from the center of mass cubed. The formula, where A is mean separation in A.U. and M is solar masses and P is the period in years:

$$P^2 = \frac{A^3}{(M_1 + M_2)}$$

FINDING DISTANCES

THE DISTANCE MODULUS

ASTRONOMY

-The distance modulus μ (mu) gives the relationship between a celestial object's **apparent magnitude**, **absolute magnitude**, and **distance in parsecs**:

$$m - M = 5\log(d) - 5$$

-If one has access to two of the three variables, one can find the value of the other. The equation can be rearranged in order to accommodate the problem at hand. The apparent magnitude m of an object like a Cepheid can be obtained by examining its light curve, if given. Its absolute magnitude M can be found via the **Period-Luminosity** relationship.

PARALLAX (STELLAR MAX DIST. ~650ly)

-Observing an object to determine its object via the displacement in its apparent displacement from two lines of sight.

-Formula for distance, d in parsecs with an angle p in arcseconds:

$$d(pc) = 1/p(arcseconds)$$

SPECTROSCOPIC PARALLAX (MAX DIST. ~10,000pc)

-One must measure the apparent magnitude of a star and know its spectral type. If on the main sequence, abs. magnitude can be approximated and then distance can be solved for using the distance modulus. Difference may be off due to **interstellar extinction**.

THE PERIOD-LUMINOSITY RELATIONSHIP

-The period of a Cepheid variable is directly related to its luminosity. The longer the period, the higher its luminosity. The relationship between its mean absolute magnitude and period can be given by the following equation, where P is measured in days:

$$M_v = (-2.43 \pm 0.12)(\log_{10}(P) - 1) - (4.05 \pm 0.02)$$

-If the mean visual (V) and near-infrared (I) magnitudes are known, the distance d in parsecs to classical Cepheids is given with the following formulae:

$$5\log_{10} d = V + (3.34)\log_{10} P - (2.45)(V - I) + 7.52$$

Or

$$5\log_{10} d = V + (3.37)\log_{10} P - (2.55)(V - I) + 7.48$$

-The relationship may also be used for objects that behave similarly to Cepheids, such as Mira and RR Lyrae variables, although adjustments will be needed. **Longest range ~25MPC**

ASTRONOMY

THE MASS-LUMINOSITY RELATIONSHIP

-An equation giving the relationship between a star's mass and its luminosity.

$\frac{L_{obj}}{L_{\odot}} \approx 0.23(\frac{M_{obj}}{M_{\odot}})^{2.3}$	*($M < 0.43M_{\odot}$)*
$\frac{L_{obj}}{L_{\odot}} = (\frac{M_{obj}}{M_{\odot}})^{4}$	*($0.43M_{\odot} < M < 2M_{\odot}$)*
$\frac{L_{obj}}{L_{\odot}} \approx 1.5(\frac{M_{obj}}{M_{\odot}})^{3.5}$	*($2M_{\odot} < M < 20M_{\odot}$)*
$\frac{L_{obj}}{L_{\odot}} \approx 3200\frac{M_{obj}}{M_{\odot}}$	*($M > 20M_{\odot}$)*

^For the value of a (the exponent), main-sequence stars are commonly 3.5

FORMULAE AND NUMBERS WORTH KNOWING

Bolometric Magnitude	$M_{star} = +4.87 - 2.5\log_{10}\frac{L_{star}}{L_{sun}}$

OBJECTS

MIRA

AKA: Omicron Ceti, SAO 129825, HIP 10826

Cetus	B-V: +1.53	RA: 02h 19m 20.79120s
Spec. Type: M7 IIIe	Dist: ~350 ly	Dec: –02° 58′ 39.4956″

A white dwarf-red giant binary system consisting of Mira A, the red giant, and Mira B, the white dwarf. Mira A is undergoing mass loss to Mira B and are separated by a distance of about 70AU. Up to 3.5Mag and as low as 8.6-10.1Mag.

W49B

AKA: SNR G043.3-00.2

Aquila	B-V: +1.53	RA: 19h 11m 09s

Supernova Remnant	Dist: ~26,000 ly	Dec: +09° 06′ 24″

Highly distorted SNR, created via a special type of supernova. About 1,000 years old and shot more matter out of its poles rather than its equator. Remnant may be a black hole, possibly the youngest in the galaxy. More barrel-shaped in terms of intense X-ray emissions from nickel and iron.

TYCHO'S SNR

AKA: SN 1572

Cassiopeia1	Disc: Nov. 1572	RA: 02h 19m 20.79120s
Supernova Remnant	Dist: ~8000-13000 ly	Dec: –02° 58′ 39.4956″

Produced as a result of a type 1a (white dwarf) supernova. Possesses a companion G2 star that is likely to have contributed the mass necessary for the supernova.

VELA SNR

AKA: SNR G263.9-03.3

Vela	Discovered:	RA: 02h 19m 20.79120s
Supernova Remnant	Dist: ~815±98 ly	Dec: –02° 58′ 39.4956″

Possesses a pulsar at its center, and exploded roughly 11000-12300 years ago. Includes NGC 2736 and is one of the closest supernovae to Earth. Helped prove that supernovae form neutron stars and its pulsar is one of the brightest in the X-ray spectrum. Rotation initially at 86ms.

G1.9+0.3

AKA:

Sagittarius	Discovered: 1985	RA: 17h 48m 45s
Supernova Remnant	Dist: ~28,000 ly	Dec: –27° 10′ 00″

The youngest-known supernova remnant in the galaxy, with its signals reaching Earth roughly 140 years ago. Exploded about 25,000 years ago as a result form a likely Type 1a supernova. Possesses synchrotron radiation for X-ray emission. Supernova remnant is extremely asymmetrical, with most X-ray radiation coming from the northern part of the remnant. Iron is also found farther out than normal.

ETA CARINAE

AKA: SAO 238429, HD 93308

Carina	B-V: +0.61	RA: 10h 45m 03.951s
Spec. Type: Blae-0	Dist: ~7,750 ly	Dec: –59° 41' 04.26"
App. Mag:		

A star system possessing an LBV with an initial mass of 150 solar masses, having lost 30 since then along with a 30 solar mass supergiant. Surrounded by the Homunculus Nebula. Possesses one of the most massive stars available for study, yet may go supernova sometime in the near future. May become a Wolf-Rayet star.

SS CYGNI

AKA: HD 206697

Cygnus	B-V: +1.53	RA: 02h 19m 20.79120s
Spec. Type: M7 IIIe	Dist: ~350 ly	Dec: –02° 58' 39.4956"

A cataclysmic variable star, of the dwarf nova variety. Consists of a close binary system with an extremely short distance (only 100,000 mi or less) and orbital period (6.5h). Outburst may change from cycle to cycle.

T TAURI

AKA: T Tau, HIP 20390

Taurus	B-V: +1.22	RA: 04h 21m 59.43445s
Spec. Type: G5V:e	Dist: ~460 ly	Dec: +19° 32' 06.4182"

A very young star (~1,000,000 years old) with highly unpredictable variations in brightness. The star itself is a protostar and possesses a very strong stellar wind, called a T Tauri wind. Higher lithium abundances than the sun, and is highly noticeable. Possesses comparatively strong spectra.

GRS 1915+105

AKA:

Aquila	B-V: +1.53	RA: 02h 19m 20.79120s
X-ray Binary	Dist: ~40,000 ly	Dec: –02° 58' 39.4956"

Microquasar. System containing black hole of about 14 solar masses with a normal star companion. First known galactic source with expulsion of material at apparently FTL velocities. Strong and variable radio emission (radio jets) and accretion disk. Heaviest of stellar mass black holes known in the galaxy.

47 TUCANAE

AKA:

Tucana	B-V: +1.53	RA: 02h 19m 20.79120s
Globular cluster	Dist: ~16.7 kly	Dec: –02° 58' 39.4956"

Globular cluster – second brightest outside of Omega Centauri with a very bright and dense core. Contains many blue stragglers near its core and multiple X-ray sources, including X-ray binaries, millisecond pulsars. No evidence of black holes in the cluster.

THE TRAPEZIUM

AKA:

Orion		RA: 02h 19m 20.79120s
Open Cluster	Dist: ~1,600 ly	Dec: –02° 58' 39.4956"

A tight grouping of half a dozen O and B type stars with masses around 15-30 solar masses, with very close distances. 4 stars, A, B, C, D, with C being the brightest and A and B being eclipsing binaries.

T PYXIDIS

AKA:

Pyxis	B-V: +1.53	RA: 02h 19m 20.79120s
Spec. Type: M7 IIIe	Dist: ~15,600 ly	Dec: –02° 58' 39.4956"

A recurrent nova and nova remnant. Binary star system consisting of a sun-like star and a white dwarf. Despite blowing up much of its accreted material, white dwarf mass is increasing and may go supernova sometime soon.

ABELL 30

AKA:

Cancer	B-V: +1.53	RA: 02h 19m 20.79120s
Planetary Nebula	Dist: ~5,500 ly	Dec: –02° 58′ 39.4956″

A planetary nebula, special due to the fact that its evolution stalled then started up again. Ejected initially into a planetary nebula. Nuclear fusion began again at its core, forming a "born-again" red giant, which then promptly exploded again. Large outer nebula about 12,500 years old, yet inner "knots" bay only be 850 years old or so.

RX J0806.3+1527

AKA: HM Cancri

Cancer	B-V: +1.53	RA: 02h 19m 20.79120s
Spec. Type: M7 IIIe	Dist: ~1600 ly	Dec: –02° 58′ 39.4956″

X-ray binary system comprised of two white dwarves orbiting each other with extremely short distances from each other (80,000km). Will likely merge in the future as they get closer and closer. Each dwarf is about half as massive as the Sun.

V1647 ORI

AKA:

Orion	B-V: +1.53	RA: 02h 19m 20.79120s
FU Ori Protostar	Dist: ~1300 ly	Dec: –02° 58′ 39.4956″

Protostar with intense X-ray emission spikes with extremely fast rotation.

V1

AKA: V1 in Messier 31

Andromeda	B-V: +1.53	RA: 00h 41m 27s
Cepheid Variable	Dist: ~2.5mly	Dec: –02° 58′ 39.4956″

A Cepheid variable star located in the Andromeda galaxy, first observed as a way to establish distances. Helped establish Andromeda galaxy as a separate object and revealed its nature as a spiral object. Ridiculously important.

NGC 1864

AKA:

Doradus	B-V: +1.53	RA: 05h 07m 35.25s
Globular Cluster	Dist: ~160,000 ly	Dec: –67° 27' 38.9"

Globular cluster with a unique planetary nebula.

NGC 3132

AKA:

Vela	B-V: +1.53	RA: 10h 07m 01.7640s
Planetary Nebula	Dist: ~2,000 ly	Dec: –40° 26' 11.060"

Eight Burst Nebula or Southern Ring Nebula, with an asymmetrical shape. Possesses a white dwarf central star. Intense UV radiation.