

Stellar Evolution – Cycles of Formation and Destruction

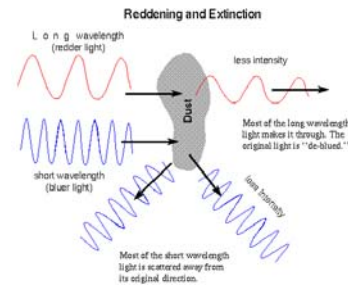
Interstellar Medium and Nebulae:



Spiral Galaxy NGC 3370 (Hubble)

NGC 3370 is a spiral galaxy similar in size and structure to our own Milky Way Galaxy. In visible wavelengths, the image is dominated by the stars and clouds of gas and dust that reside in and define the spiral arm structure. Not obvious in the image are the dust grains, and atomic and molecular gas that comprise the tenuous interstellar medium (ISM) interspersed between the stars. The extremely low average density of the interstellar medium - about one atom per cubic centimeter - is nearly a perfect vacuum; however, due to the enormous amount of space between the stars, the ISM constitutes ~20-30% of the mass of a galaxy. The interstellar medium is primarily hydrogen and helium left over from the Big Bang, enriched with heavier elements from the nuclear fusion of elements in the cores of previous generations of stars. The interstellar medium is immersed in radiation, magnetic fields and cosmic ray particles, and has an average temperature of 1,000,000 K.

The interstellar dust particles are extremely small – usually less than about one thousandths ($1/1000^{\text{th}}$) of a millimeter across – and composed mostly H, C, O, Si, Mg and Fe in the form of silicates, graphite, ices, metals and organic compounds. The size of the dust grains is the same size as the wavelength of the blue portion of the visible spectrum; therefore, the dust grains scatter blue light. Since the light that reaches Earth from distant objects is depleted in blue wavelengths by the dust, the resultant transmitted light appears redder than it actually is. This is called interstellar reddening. The dust particles also absorb incident light, heat up, and emit in the infrared - resulting in the dimming of starlight. This is called interstellar extinction, and dims the light from deep sky objects.



Nebulae are denser agglomerations of interstellar gas and dust; the main types of nebulae are diffuse, reflection, and absorption. An emission nebula produces an emission spectrum because of energy that has been absorbed from one or more hot luminous stars that excite the hydrogen gas. The ultraviolet (UV) radiation from the massive hot stars ionizes the hydrogen - it strips electrons from the hydrogen atoms - by the process of photoionization. The free electrons combine with protons, forming hydrogen atoms, and emit a characteristic series of emission lines as they cascade down through the energy levels of the atoms. The visible radiation in these lines imparts to these regions their beautiful reddish-colored glows. These regions of ionized hydrogen gas (called HII regions) have typical temperatures of ~10,000 - 20,000 K, and a density of ~10 atoms/cm³. In the image to the right is the emission nebula M42, located in the constellation of Orion. The hot luminous stars to the left of the nebula are ionizing the interstellar hydrogen, and protons and electrons are recombining and emitting red light.



M42 (Stephan Seip)



Witch Head Nebula (Gary Stevens)

A nebula that is mainly composed of cool interstellar dust that reflects and scatters light from nearby stars is called a reflection nebula. They are usually blue because the scattering is more efficient for blue light by the dust particles. The [Witch Head Nebula](#) to the left is a reflection nebula, and is also glowing due to the ultraviolet radiation from the nearby hot, blue massive star Rigel in the constellation of Orion. Absorption nebulae are physically very similar to reflection nebulae; they look different only because of the geometry of the cloud of dust, the light source and Earth. Absorption, or dark nebulae, are simply blocking the light from the source behind them.

The [Horsehead Nebula](#) (Barnard 33) is visible only because it is silhouetted against the emission nebula behind it. Emission, reflection, and absorption nebulae are often seen within the same field of view. The image of [NGC 6559](#) below, a bright red emission nebula, also contains a reflection nebulosity surrounding the two hot young stars located in the left central portion of the image. The image also contains dark clouds and filaments, highlighted against the bright emission nebula.



Horsehead Nebula (USNO)

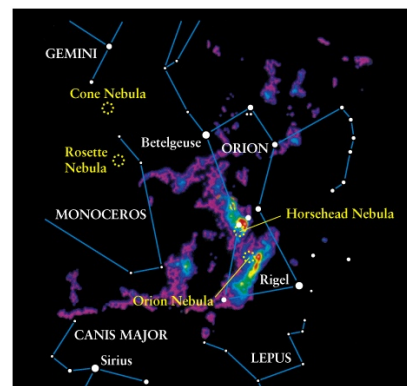


NGC 6559 (Adam Block, KPNO)

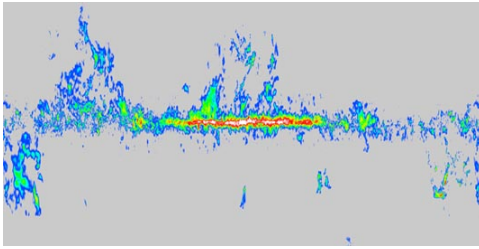
Emission and reflection nebulae are associated with star formation regions since they are caused by ultraviolet emissions from hot, young stars; however, stars do not form in these types of nebulae. Emission and reflection nebulae are too warm and diffuse for stars to form.

Giant Molecular Clouds and Protostars:

Huge complexes of interstellar gas and dust left over from the formation of the galaxy, called molecular clouds, are composed mostly of molecular hydrogen. These clouds are the coolest (10 to 20 K) and densest (10^6 to 10^{10} particles/cm³) portions of the interstellar medium. Since these clouds are cooler than most places, they are perfect locations for star formation. The molecular clouds are puffy and lumpy, with diameters ranging from less than 1 light-year to about 300 Light Years and contain enough gas to form from about 10 to 10 million stars like our Sun. Molecular clouds that exceed the mass of 100,000 suns are called Giant Molecular Clouds (GMC's). A typical full-grown spiral galaxy contains about 1,000 to 2,000 Giant Molecular Clouds and many smaller ones. Such clouds were first discovered in our Milky Way Galaxy with radio telescopes about 25 years ago. Since the molecules in these clouds do not emit optical light, but do release light at radio wavelengths, radio telescopes are necessary to trace the molecular gases and study their physical properties. The image above shows the distribution of GMC's within the Orion and neighboring constellations; produced by radio

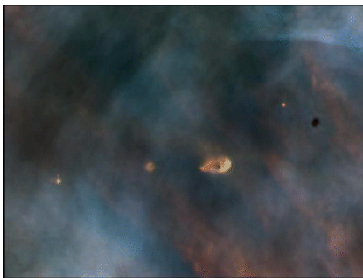


mapping of carbon monoxide (CO) gas. A map of stars, bright nebulae, and cold clouds within 2000 LY of the Orion spiral arm of the Milky Way Galaxy can be seen at <http://www.anzwers.org/free/universe/2000lys.html>



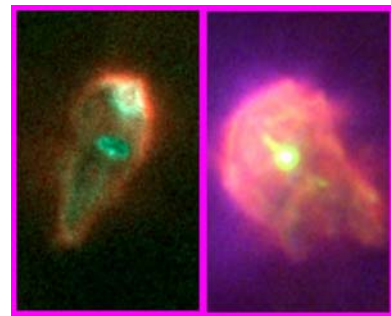
Milky Way Galaxy Molecular Map (CFA, Harvard)

Star-forming molecular clouds are mostly found along spiral arms, as seen in the [CO molecular map](#) showing the distribution of these clouds in the Milky Way Galaxy. Individual giant molecular clouds are internally violent and turbulent. The self-gravitational energy of the clumps is counter-balanced by pressure from both the supersonic velocity of the gases and magnetic field lines. Perturbations from the spiral density wave within the spiral arm structure, collisions between clouds, supernovae shockwaves, and nearby massive star formation are some of the possible triggers that eventually cause an imbalance within the GMC's and the clumps begin to collapse. Individual stars within clumps form within their own smaller gaseous structures, called cores.



Proplyds in Orion (Hubble)

As a gas clump collapses it heats up due to friction as the gas particles bump into each other. The energy the gas particles had from falling under the force of gravity (gravitational potential) gets converted to heat (thermal) energy. The gas clump becomes warm enough to produce infrared and microwave radiation. During the initial collapse, the clump is transparent to radiation and the collapse proceeds fairly quickly. As the clump becomes more dense, it becomes opaque. Infrared radiation is trapped, and the temperature and pressure in the center begin to increase. As the clump starts evolving into a protostar, at first it only has about 1% of its final mass; however the envelope of the star continues to grow as infalling material is accreted. After a few million years, thermonuclear fusion begins in its core, and a strong stellar wind is produced which stops the infall of new mass. Other material in the disk may coalesce to form other stars and/or planets. Protostars reach temperatures of 2000K to 3000K - hot enough to glow red - but the cocoon of gas and dust surrounding them blocks visible light from escaping. The [proplyds in Orion](#) are protostars embedded within [protoplanetary disks](#). The close-up of two of these young disks in Orion reveals the torturous conditions they must face while trying to grow into full-fledged planetary systems. Ultraviolet radiation from one of Orion's nearby hot stars is rapidly destroying the disks surrounding the protostars. Only ~10% if all protostars survive the harsh conditions within stellar nurseries to become stars.



Protoplanetary Disks (Hubble)

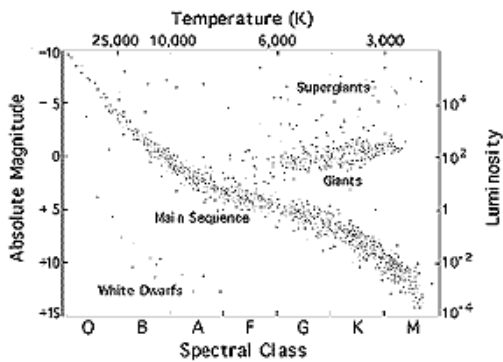
Introduction to the H-R Diagram:

The evolutionary sequences for stars are describing their position on a diagram called the Hertzsprung-Russell (H-R) diagram. Most stages of stellar evolution, beginning with

protostars, have a specific position on the H-R diagram. The different branches of the H-R diagram described below will be referred to throughout the descriptions of the evolutionary sequences for different mass stars that follow.

You are probably familiar with the periodic table of the elements. The periodic table is an arrangement of all the known elements in order of increasing atomic number. The reason why the elements are arranged as they are in the periodic table is to fit them all, with their widely diverse physical and chemical properties, into a logical pattern. The vertical lines of elements, called groups, and the horizontal lines of elements, called periods, are chemically similar, and

share a common set of characteristics. The elements are also arranged into blocks that share commonalities. The arrangement of the elements in the periodic table also shows the periodicity and trends of some properties, such as electron configuration, metallicity, atomic radii, and melting points. By looking at the location of any individual element in the table, you automatically know several characteristics and properties of that element, as well as what types of chemical bonds it forms, and the chemical reactions it will undergo.



The Hertzsprung-Russell diagram, or H-R diagram, is the periodic table of the stars. It was discovered that when the luminosity (absolute magnitude, or brightness) of stars is plotted against their temperature (stellar classification) the stars are not randomly distributed on the graph but are mostly restricted to a few well-defined regions. The stars within the same regions share a common set of characteristics, just like the groups, periods, and blocks of

elements in the periodic table. As the physical characteristics of a star changes over its lifetime, it's position on the H-R diagram changes also – so the H-R diagram can also be thought of as a visual plot of stellar evolution. It is a graphical tool that astronomers use to classify stars. From the location of a star on the graph, the luminosity, spectral type, color, temperature, mass, chemical composition, age, and evolutionary history is known.

The Main Sequence: ~90% of all stars occupy the diagonal band running from the upper left corner (hot, luminous stars) to the lower right corner (cool, dim stars) of the H-R diagram. Stars become main sequence stars when the process of thermonuclear fusion - hydrogen to helium - stabilizes. These stars are in hydrostatic equilibrium - the outward radiation pressure from the fusion process is balanced by the inward gravitational force. When the transition from a protostar to the main sequence star occurs, the star is called a Zero Age Main Sequence star (ZAMS). The determining factor of where a star is located on the main sequence is mass. The Sun is a G spectral class star with an effective surface temperature of ~5800K. Since the luminosity and mass of all other stars are measured relative to the Sun, it has one solar luminosity and one solar mass. The O and B stars are the hottest and most massive, and the K and M stars are the coolest and least massive stars. The O and B stars are sometimes referred to as early sequence stars, and the K and M stars as late sequence stars. These terms refer to stars more massive (early sequence) than the Sun or less massive (late sequence) than the Sun. All one solar mass stars, for

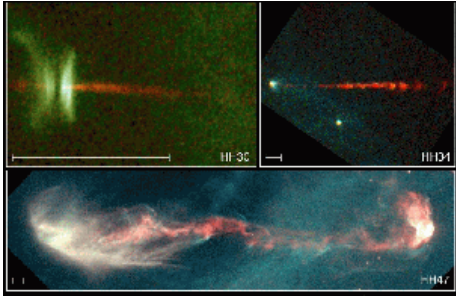
instance, occupy the same position on the main sequence as the Sun, and they stay in that location, with that specific relationship of temperature and absolute magnitude, until the star runs out of hydrogen and the fusion of hydrogen nuclei to helium nuclei stops. The mass-luminosity relationship for main sequence stars is defined as: $L/L(\text{Sun}) \sim [M/M(\text{Sun})]^4$. All main sequence stars with a mass less than ~ 8 solar masses are sometimes referred to as dwarf stars, with the coolest, least massive stars in the lower right corner called red dwarfs. The more massive the star, the faster the rate of fusion, and the less time it remains on the main sequence. The amount of time that a star spends on the main sequence is also a function of its mass and luminosity and is defined as: $T(\text{years}) = 10^{10} M/L$.

The Giant Branch: Red giants are luminous, cool giant stars in spectral classes F, G, K, and M located in the middle right portion of the H-R diagram, above the main sequence. As the central core of a main sequence star with a mass from ~ 0.8 to 8 solar masses runs out of hydrogen, radiation pressure no longer balances gravity and the star begins to collapse. There is still hydrogen in the outer layers surrounding the helium core of the star; however the temperature is not high enough for this hydrogen to fuse. As the star begins to contract, the core gets hot enough to start a thin shell of hydrogen fusion around the helium core. The increase in radiation pressure causes the star's outer atmospheric layers to expand. As the surface of the star increases, so does its apparent brightness. As the surface (photosphere) increases, it becomes cooler, and the color of the star becomes redder. Eventually the hydrogen in the shell becomes depleted and the star begins to contract once again, and this time the temperature becomes hot enough to start helium fusion. The outer layers expand even further, becoming cooler and redder. Giant stars fuse elements up to carbon. Most of these stars go through a Mira variable instability stage with a periodic light curve of $\sim 80 - 1000$ days. Stars that have evolved to the giant branch are commonly referred to as red giants. Eventually these red giants will shrug off a planetary nebula and leave a white dwarf core remnant. There is no relationship among mass and luminosity on the giant branch.

The Supergiant Branch: Stars greater than ~ 8 solar masses evolve onto the supergiant branch, located in the extreme upper right corner of the H-R diagram. These red supergiants are extremely luminous and cool, due to their expanded size. Their spectral types range from B - the massive stars just leaving the main sequence - through M, as they finish their transition to the supergiant branch. NOTE: The O and B stars on the main sequence are sometimes referred to as blue supergiants, not to be confused with the highly evolved and aging red supergiants located on the supergiant branch. Because of the mass of these stars, the fusion of heavier and heavier elements continues through neon, magnesium, silicon, sulfur, iron and nickel. Each time a new element is created the star becomes larger and redder. (Some stars with a mass of ~ 8 solar masses move through the Cepheid variable instability strip and become pulsating Cepheids with a period of 1 - 70 days). Eventually most of these stars reach the supergiant branch and undergo a Type II supernovae explosion and core collapse, leaving behind a pulsar, neutron star, magnetar or black hole. Some hyper-massive stars collapse into black holes without a supernova event, and some of the less massive giant stars manage to avoid a supernova event and become white dwarfs. [NOTE: there are exceptions to some of these evolutionary sequences, and the associated masses are "ballpark" numbers only - there is much to learn about the evolutionary history of stars.]

The White Dwarf Branch: The white dwarf branch is located in the lower left corner of the H-R diagram. This branch consists of the end products of stellar evolution for mid-sized stars with an initial mass of ~0.8 to 8 solar masses. All white dwarfs are extremely hot; however they have a very low absolute magnitude because they are very small. They have a size that does not exceed 1.4 solar masses - the Chandrashekar limit. Spectral types for white dwarfs range from O to G as they slowly radiate away their energy.

Young Stellar Objects:



HH Objects (Hubble)

Any star that has evolved past the protostar stage (i.e. is shining by way of internal nuclear reactions) but has yet to arrive on the main sequence is called a Young Stellar Object (YSO). YSO's come in a variety of forms depending on their age, mass, and environment, and include Herbig-Haro objects, T Tauri stars, and, in general, immature stars prone to irregular brightening, embedded in nebulosity, and associated with bipolar outflows. The montage of

Hubble [HH objects](#) provides a dramatically clear look at collapsing circumstellar disks of dust and gas that build stars and provide the

ingredients for planetary systems. Blowtorch-like jets of hot gas are funneled from deep within these embryonic systems, and machine-gun like bursts of material are fired from the young stellar objects at speeds of nearly a half-million kilometers per hour. The Herbig-Haro object [HH111](#) shows the fast-moving jets of material from a newborn star colliding with the interstellar medium. As the bipolar flow from a young star plows into the surrounding gas, it generates strong shock waves that heat and ionize the gas. In the cooling gas behind the shock front, electrons and ions recombine to give an emission line spectrum characteristic of Herbig-Haro objects. All known Herbig-Haro objects have been found within the boundaries of dark clouds, and are strong sources of infrared radiation.



HH 111 (Hubble)



Trifid Nebula (Hubble)

The [Trifid Nebula](#) is one of the most prominent nebulae in the night sky. Radiation from the powerful central star is eating away at the surrounding dense interstellar material. The field of view of this Hubble image includes a region of star formation that will be destroyed by the advancing ionization front in the next ~20,000 years. A prominent jet from a young stellar object and a long finger with a possible young



Trifid EGG with jet

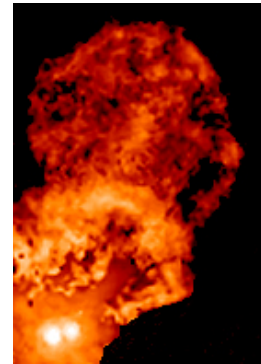
stellar object at its tip are apparent in the image. The [stellar jet](#) is emerging from the wall of a cloud in the Trifid Nebula. The jet is remarkable because, unlike most stellar jets, it can be seen along its entire length. This is because the jet is being lit up by radiation from the massive, luminous star that powers the Trifid. The tip of a finger-like Evaporating Gaseous Globule, or "[EGG](#)", pointing back



Trifid Stellar Jet

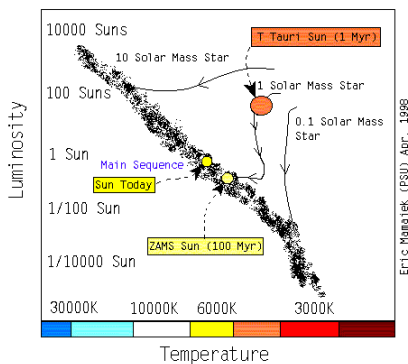
at the Trifid's central star. A tiny jet emerging from the EGG and a patch of reflected light suggest that a young stellar object is buried in the tip of the jet. This young stellar object was uncovered a few tens of thousands of years ago as radiation from the Trifid's central star disrupted the dense cloud from which the star formed.

A **T Tauri** star is a very young, lightweight star, less than 10 million years old and under 3 solar masses, that it still undergoing gravitational contraction; it represents an intermediate stage between a protostar and a mid-mass main sequence star like the Sun. T Tauri stars are found only in nebulae or very young clusters, have low-temperature (G to M type) spectra with strong emission lines and broad absorption lines. They are more luminous than main sequence stars of similar spectral types, and they have a high lithium abundance, which is a pointer to their extreme youth, as lithium is rapidly destroyed in stellar interiors. T Tauri stars often have large accretion disks left over from stellar formation. Their erratic brightness changes may be due to instabilities in the disk, violent activity in the stellar atmosphere, or nearby clouds of gas and dust that sometimes obscure the starlight. Two broad T Tauri types are recognized based on spectroscopic characteristics that arise from their disk properties: classic T Tauri and weak-lined T Tauri stars. Classical T Tauri stars have extensive disks that result in strong emission lines. Weak-lined T Tauri stars are surrounded by a disk that is very weak or no longer in existence. The weak T



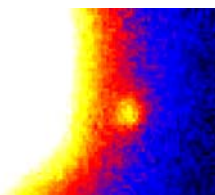
XZ Tauri (Hubble)

Tauri stars are of particular interest since they provide astronomers with a look at early stages of stellar evolution unencumbered by nebulous material. Some of the absent disk matter may have gone into making planetesimals, from which planets might eventually form. According to one estimate, about 60% of T Tauri stars younger than 3 million years may possess dust disks, compared with only 10% of stars that are 10 million years old. T Tauri stars represent an evolutionary stage between protostar and main sequence and are located just above the main



sequence on the H-R diagram.

Brown Dwarfs & Low Mass Stars:



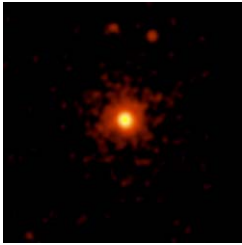
Gliese 229B (Palomar)

If a protostar forms with a mass less than 0.08 solar masses, its internal temperature never becomes high enough for thermonuclear fusion to begin. This failed star is called a brown dwarf, halfway between a planet (like Jupiter) and a star. A star shines because of the thermonuclear reactions in its core, which release enormous amounts of energy by fusing hydrogen into helium. For the fusion reactions to occur, though, the temperature in the star's core must reach at least three million K. And because core temperature rises with gravitational pressure, the star must have a minimum mass: about 75 times the mass of the planet Jupiter, or



Brown Dwarfs in Orion (Hubble)

about 8 percent of the mass of our sun. A brown dwarf, like [Gliese 229B](#) pictured above, just misses that mark; it is heavier than a gas giant planet but not quite massive enough to be a star. Brown dwarfs still emit energy, mostly in the infrared, due to the potential energy of collapse converted into kinetic energy. There is enough energy from the collapse to cause the brown dwarf to shine for more than ~15 million years. Brown dwarfs eventually radiate all their heat into space and fade away. The composite Hubble image shows the Trapezium stars (optical) within the Orion Nebula combined with an infrared image that shows a swarm of [brown dwarfs](#).



Proxima Centauri (Chandra)

All through the long life of a low mass star, the relentless compression of gravity is balanced by the outward pressure from the nuclear fusion reactions in the core. Eventually, the hydrogen nuclei in the core is all converted to helium nuclei and the nuclear reactions stop. No stellar evolution takes place in stars with less than 0.8 solar masses. The time it takes for low mass stars to use up all their hydrogen fuel is longer than the current age of the universe (about 14 billion years). These extremely low mass stars are called red dwarfs, and they are located on the lower right corner of the main sequence on the H-R Diagram. [Proxima Centauri](#), the nearest star to the Sun, is a red dwarf star.

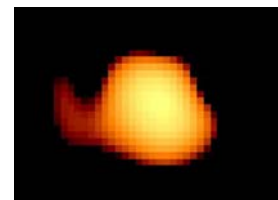
Mid-Sized Stars:



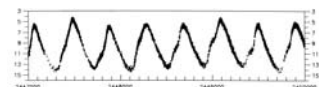
Sun (SOHO)

Thermonuclear fusion in stars with masses between ~0.8 and 8 solar masses, similar to our [Sun](#), produces the outward radiation pressure to counterbalance gravitational forces for approximately ten billion years. When all the hydrogen nuclei have been converted to helium nuclei and fusion stops, gravity takes over and the core begins to collapse. The layers outside the core collapse too - the layers closer to the center collapse more quickly than the ones near the stellar surface. As the layers collapse, the gas compresses and heats up. The temperature becomes high enough for helium nuclei to fuse into carbon and oxygen nuclei, with hydrogen fusing in a thin shell

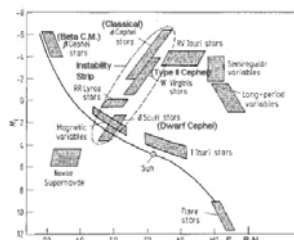
surrounding the core. The outer layers expand to an enormous size and the star is now called a red giant. The star brightens by a factor of ~1,000 to 10,000, and the surface temperature of the extended envelope drops to about 3,000K - 4,000K, giving the star its reddish appearance. A strong wind begins to blow from the star's surface, carrying away most of the hydrogen envelope surrounding the star's central core. During the final shedding of its envelope, when the mass loss is greatest, the star pulsates - the surface layers expand and then contract in repeating cycles - with periods from several months to more than a year. During this pulsating stage the star is called a [Mira](#)



Mira (Hubble)



Mira Light Curve



variable star.

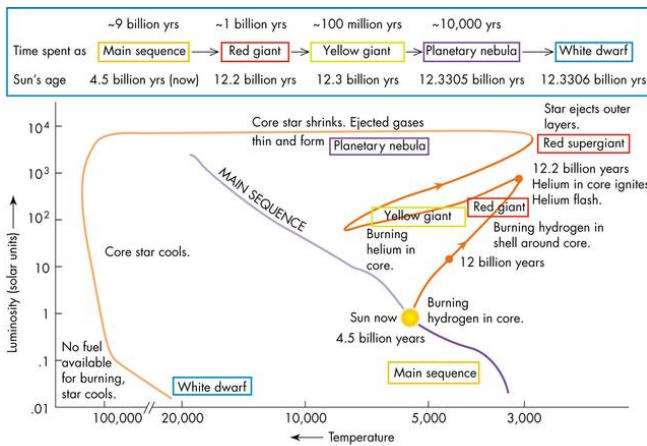
The pulsations of Mira variable stars result in a change in the magnitude, or brightness, of the star. A plot of the change in brightness over time is call a light curve. During this stage, as mid-sized stars evolve to the giant branch, they move through an area referred to as the Mira instability strip - on the H-R

diagram shown here this area is further divided into long-period and semiregular variables. Not all stars go through these stages of variability.



Helix Nebula (Hubble)

Eventually, the material ejected by the star forms an envelope of gas called a **planetary nebula** which expands into the surrounding interstellar medium at $\sim 17\text{-}35$ km/hr. The core of the star left in the center of the planetary nebula is called a white dwarf. The planetary nebula is very tenuous, and becomes so thin that after $\sim 50,000$ years it is no longer visible - therefore all planetary nebulas that we see are very young, less than $\sim 50,000$ years old. The white dwarf is extremely dense. It is held in equilibrium with gravity by electron degeneracy pressure. The repulsive forces of the electron clouds of the individual atoms are strong enough to stop any further gravitational contraction. The mass limit for a white dwarf to remain in equilibrium between gravity and electron degeneracy pressure is 1.4 solar masses - the Chandrasekhar limit. Eventually the white dwarf will radiate all of its remaining energy away and become a black dwarf - a cold, dark mass. The universe is not old enough for any white dwarf to have become a black dwarf, so black dwarfs are not considered as part of the evolutionary stage of a star.



This H-R diagram shows the evolutionary track of the Sun, which is halfway through its lifetime of ~ 9 billion years on the main sequence. It is a spectral type G star, has an effective surface temperature of $\sim 5800\text{K}$, and one solar luminosity. When the Sun runs out of hydrogen fuel in its core and fusion stops, it will begin its journey to the red giant branch. The Sun will contract, heat up until a shell of hydrogen is fusing around the helium core, and become

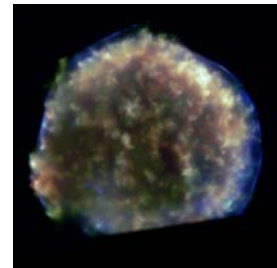
cooler, $\sim 3000\text{K}$, reddish in color, and more luminous - in excess of 500 solar luminosities. After \sim one billion years, the hydrogen shell fusion stops and the Sun contracts again, becoming less luminous, hotter, and less red in color. During this phase it is sometimes referred to as a yellow giant. The contraction will cause the core to heat up until helium fusion begins in the core. The fusion of helium nuclei to carbon nuclei causes the Sun to expand again, becoming more luminous. The core will contract again when it runs out of helium and fusion stops again; this time there is not enough mass for the shrinking core to achieve the temperature necessary for the fusion of carbon to begin. The Sun will throw off its outer atmospheric layers into a planetary nebula and the remaining carbon core - called a white dwarf - will then reside on the white dwarf branch of the H-R diagram. The white dwarf is very dim and very hot - with a temperature of $\sim 20,000\text{K}$. The white dwarf will radiate away its heat over the next ~ 12 billion years and become a burnt out carbon cinder called a black dwarf.



A white dwarf is not the end produce is the stellar evolution of a mid-sized star if it is in a [binary system](#). Suppose two stars, one with one solar mass and the other with five solar masses are in a binary system. The five solar mass star runs out of hydrogen faster than its less massive companion, becomes a red giant, shrugs off a planetary nebula, and collapses into a white dwarf. Eventually the companion

star runs out of hydrogen and enters *Dana Berry, Artist* the red giant stage. The outer layers of the red giant are loosely held by the star, and the extreme gravitational field of the white dwarf starts pulling the material from the red giant into an accretion disk around the white dwarf. The mass transfer continues, with the material orbiting the white dwarf in the accretion disk. Friction slows the matter's orbital motion, which causes the matter to spiral through the disk down to the surface of the white dwarf. The falling and spiraling of the matter toward the white dwarf releases large amounts of gravitational energy and heats the accretion disk.

The white dwarf is predominately carbon and oxygen, and accretes matter from its companion relatively rapidly. Consequently, the white dwarf grows in mass. When the accretion has raised the white dwarf's mass to the critical mass of 1.4 solar masses, the density and temperature in the center of the white dwarf become so severe that carbon starts fusing explosively. Within one second the fusion front moves all the way to the surface, making the entire white dwarf one huge nuclear catastrophic event. The white dwarf explodes and is completely destroyed. There is no stellar remnant. All of the core's matter - namely, the products of the nuclear fusion (iron, nickel, silicon, magnesium, and other heavy elements) plus remaining carbon and oxygen -



Tycho's

SNR (Chandra) are ejected into space at speeds upwards of 48,000,000 km/hr. [Tycho's supernova remnant](#) is the result of a Type Ia supernova event; the core was completely destroyed by the explosion.

Massive Stars:



not even exist for the

M7 Open Cluster in Scorpius (NOAO)

Massive star formation seems to take place in clusters, like the open cluster, M7. Studying the distribution of massive stars and how they form is complicated because most of their energy is emitted at far-ultraviolet wavelengths that are not accessible from Earth, and they have short main sequence lifetimes; stars greater than 40 solar masses may not even finish their assembly until after fusing a significant portion of their core hydrogen, so a zero-age main sequence stage may

most massive stars.

Massive stars are low in number but make a large contribution to the properties of galaxies. They are fundamental to the production of the heavy elements and to the energy balance in the interstellar medium. Massive stars regulate the rate of star formation on large scales through feedback via intense winds, radiation and, finally, through



Eagle Nebula (NOAO)

supernova explosions. Most stars are formed in the neighborhood of a massive star, so they influence the rate of low-mass star formation. The [Eagle Nebula](#) is a major star-forming region. Star formation will stop after a relatively small number of stars have been formed. That's because the stellar nursery is blown away by some of the newly formed stars. The hottest of these stars heat the surrounding molecular gas, break up its molecules, and drive the gas away. As the gas and dust clears, the previously hidden young stars become visible, and the molecular cloud and its star-forming capability cease to exist. So, ironically, the same climate that is conducive to star formation also may shut off the star formation process. Young stars are very hot and can heat the molecular gas to more than 800 K, which is an unfavorable climate for star formation. When the temperature exceeds about 1900 K, the gas molecules break down into atoms.



Orion Nebula (CFHT)

The [Orion Nebula](#) (M42) is ~1500 LY away, and the closest stellar nursery. The Orion Nebula is an emission nebula, excited by four young hot luminous stars in its center, called the [Trapezium](#). The trapezium stars are ~2,000,000 years old. Eventually, the entire Orion complex, which includes the Orion Nebula, the trapezium, and the Horsehead nebula, will slowly disperse over the next



Trapezium in Orion (Hubble)

~100,000 years. Eventually this area will resemble the Pleiades - an open cluster of young, hot stars that formed together, produced intense ultraviolet radiation that blew away the gas clouds surrounding them, and began slowly drift apart over time.

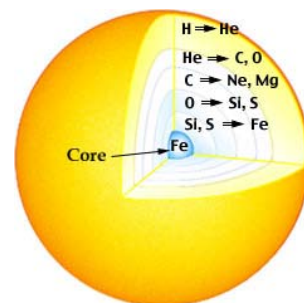


N44F (Hubble)

This image of [N44F](#) captures the gas cavity carved by the stellar wind and intense ultraviolet radiation from a hot young star. This young star was once buried deep within a cold dense molecular cloud. The cloud fragmented and condensed, forming a core which became a protostar. Eventually the protostar became hot enough for thermonuclear fusion to begin, and the hydrogen nuclei in the core started fusing into helium nuclei. After the core

hydrogen has been depleted in these massive stars (greater than ~8 solar masses) helium begins fusing into carbon and oxygen nuclei. The carbon-oxygen core contracts and heats until it is hot enough for carbon and oxygen to start the fusion process. Their fusion yields neon, magnesium, silicon, and sulfur nuclei. Eventually, silicon and sulfur fuse in the star's core to form iron, nickel, and other nuclei of similar atomic weight.

The star's structure now resembles an onion. The central core of the onion consists of iron nuclei. Surrounding it is a shell in which silicon and sulfur are fusing, adding more iron nuclei to the iron core. In additional levels further out, lighter elements fuse - oxygen, carbon, helium, and hydrogen. The iron core is very compact and cannot ignite to induce further nuclear fusion. Nuclear fusion, just like chemical burning, is





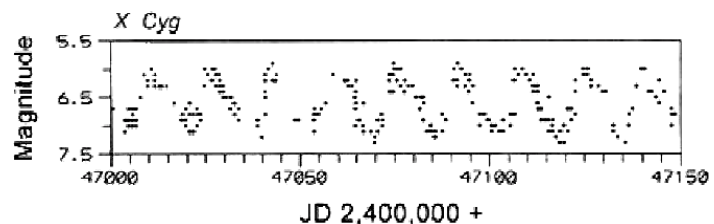
possible only if the reactions release energy. The fusion of iron with other nuclei to make still heavier nuclei requires an input of energy - it is an endothermic reaction. The energy required to manufacture elements heavier than iron becomes available only during the catastrophic collapse of the star's core and the violent explosion of the star's outer envelope that is about to occur. The cluster of hot stars in the lower right corner of Hodge 301, located within the Tarantula Nebula, is rapidly approaching collapse. This massive star-forming region is in the Large Magellanic

Cloud, a galaxy ~180,000 LY away. As the hydrogen fuel begins to run out, massive stars leave the main sequence of the H-R diagram and start evolving towards the supergiant

Hodge 301(Hubble)

branch. The transition to the supergiant branch is not smooth, and the stars expand and contract as the fusion process changes from one type of nuclei to the next. Many of these stars pulsate because they are not in hydrostatic equilibrium: the force of gravity acting on the outer mass of the star is not quite balanced by the interior radiation pressure pushing outwards. If a star expands as a result of increased gas pressure, the material density and pressure decrease until the point that hydrostatic equilibrium is reached and then overshot, owing to the momentum of the expansion. At this point the star is transparent and photons can escape. Then gravity dominates, and the star begins to contract. The momentum of the infalling material carries the contraction beyond the equilibrium point. At this point the star becomes opaque and photons are trapped and the star is dimmer. The pressure again becomes too high, and the cycle starts over again. They system acts as an oscillator. This type of star is called a variable star, because the star changes its brightness, or magnitude, as it pulsates. One type of massive pulsating variable star is called a Cepheid. Most massive stars pass through the Cepheid instability strip of the H-R diagram as they progress towards the red supergiant branch.

Cepheids have a repeating cycle of change that is periodic - as regular as the beating of a heart. Observations of the changes in apparent magnitude of variable stars - including Cepheids - are plotted as the apparent magnitude versus time, usually in Julian Date (JD). The resulting graph is called a light curve. The light curve for the Cepheid variable star X Cyg (located in the constellation Cygnus) is shown below. Each data point represents one observation. Once many observations have been plotted, important information can be obtained from the resulting pattern of changing magnitudes. The period for X Cyg is the amount of time it takes for the star to go through one complete cycle from maximum magnitude (brightness), through minimum magnitude (dimkest), and back to maximum magnitude (brightness.)



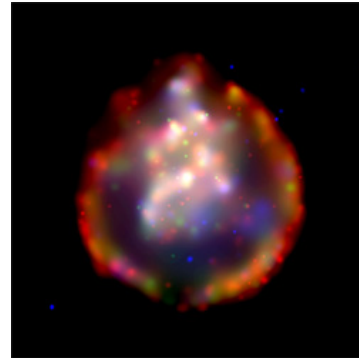
[<http://www.aavso.org/vstar/types.shtml>]



The mass of the star's iron core approaches 1.4 solar masses - the Chandrasekhar Limit - due to the continued silicon and sulfur fusion in the thin shell adjacent to the iron core, and the continued fusion of iron requires more energy than is available. Once the Chandrasekhar Limit is reached, the

electron degeneracy pressure of the atoms within the core is *Sher 25 (ESO)* no longer able to stop to further collapse of the star;

radiation pressure is no longer able to support the core against gravity and the iron core collapses. In less than a second, the core collapses from a diameter of ~8000 kilometers to ~19 kilometers - the collapse happens so fast that the outer layers have no time to react or collapse along with the core. The energy released during core collapse is unimaginable - more energy than is produced by 100 stars like the Sun during their entire lifetimes of more than 10 billion years! Most of the energy released during collapse is carried off into space by neutrinos; however a small fraction of the energy triggers the accompanying supernova explosion. It is possible that *Sher 25* will be the next observable supernova event. The supernova Remnant *SNR 0103-72.6* occurred



SNR 0103-72.6 (Chandra)

~10,000 LY away in the Small Magellanic Cloud - a neighboring galaxy. The X-ray image shows great detail within this remnant, even though it is ~190,000 LY away. It is easier to study remnants in other galaxies, because within the Milky Way these objects are obscured by the gas and dust within the spiral arms.



SN1987A (AAO)

The core collapses so fast that it momentarily goes past its equilibrium point and instantaneously rebounds. The innermost layers of the star are still in-falling and meet the rebounding core, creating a super strong shock wave that runs outward through the layers towards the star's surface. The shock wave heats the outer layers, inducing explosive nuclear burning, and ejects the outermost layers in excess of speeds of ~16 million kilometers per hour. The energy released by the shockwave manufactures elements heavier than iron. When the shock wave reaches the star's surface, it heats the surface layers and brightens them – within a day or two the exploding star becomes brighter than a billion Suns. The *SN1987A* supernova event in the Large Magellanic Cloud galaxy was the first witnessed supernova event since Johannes Kepler recorded his in 1604. The

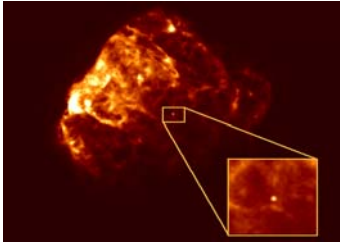


Cas A (Hubble)



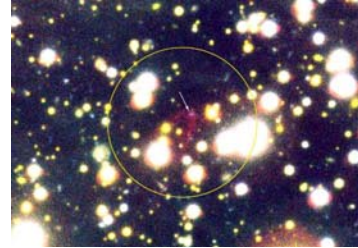
Veil Nebula (NOAO)

expanding gaseous shell plows into the surrounding interstellar medium, and pushes, compresses, and intermingles with it. The material, rich in heavy elements, now seeds the interstellar space surrounding the star, and may trigger the formation of a new generation of stars. The images of the *Veil Nebula* and *Cas A* show supernovae remnants plowing through space, carrying the newly created elements into the interstellar medium. The core collapse of a massive star is a Type II supernova event. The stellar end product left behind depends upon the initial mass of the star, and is either a neutron star, pulsar, magnetar, or black hole.



Puppis A Remnant (ROSAT)

Neutron stars have passed the 1.4 solar mass Chandrasekhar limit, and are not held in equilibrium by electron degeneracy pressure. The repulsive force between electrons is not strong enough to balance gravity in a star that begins with more than ~8 solar masses and has a core remnant between 1.4 and 2.5 solar masses. The collapsing core is so massive that the electrons are forced into the atomic nuclei where they combine with protons and become neutrons. Neutron stars are held in equilibrium with neutron degeneracy pressure (strong nuclear force) which provides the pressure to stop gravity from contracting the core any further. The Type II supernova remnant [Puppis A](#) contains a neutron star. [RXJ 1856.5-3754](#) is the closest neutron star.



RX J1856.5-3754 (ESO)



G292.0+1.8 (Chandra)

Pulsars are spinning neutron stars that have jets of particles moving almost at the speed of light streaming out from the magnetic poles. These jets produce very powerful beams of high energy particles that emit x-rays. For a similar reason that "true north" and "magnetic north" are different on Earth, the magnetic and rotational axes of a pulsar are also misaligned. Therefore, the beam of particles and x-rays from the jets sweep around as the pulsar rotates, just as the spotlight in a lighthouse does. Like a ship in the ocean that sees only regular flashes of light, we see pulsars turn on and off as the beam sweeps over the Earth. The oxygen-rich supernova [G292.0+1.8](#) contains a pulsar. Neutron stars have very intense magnetic fields, about 1,000,000,000,000 times stronger than Earth's own field. The combination of this strong magnetic field and the rapid rotation of the neutron star produces extremely powerful electric fields, with electric potential in excess of 1,000,000,000,000 volts. Electrons are accelerated to high velocities by these strong electric fields. These high-energy electrons produce radiation in two general ways: as a coherent plasma the electrons work together to produce radio emissions, and individually the electrons interact with photons or the magnetic field to produce high-energy emission such as optical, X-ray and gamma-ray. The pulses of radiation match the rate of the rotation of the neutron star.

[Magnetars](#) are neutron stars that have super strong magnetic fields, about 100 trillion times as strong as the Earth's magnetic field. These fields are so intense that the solid neutron star crust buckles and shifts under its influence. The resulting star quakes could repeatedly generate brief flashes of hard X-rays and soft gamma-rays - giving rise to the rare but



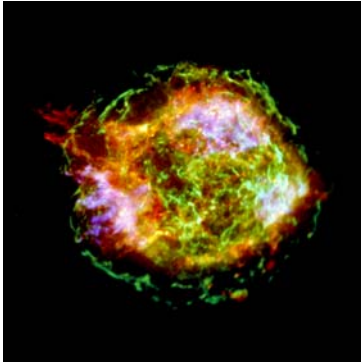
Magnetar Illustration, Robert Mallozzi

mysterious "soft gamma repeaters" - because magnetars seem to be rotating too slowly to produce the observed

energy output. The Hubble image of [N49](#), a Type II supernova remnant in the Large Magellanic Cloud,

N49 (Hubble)

contains a magnetar.

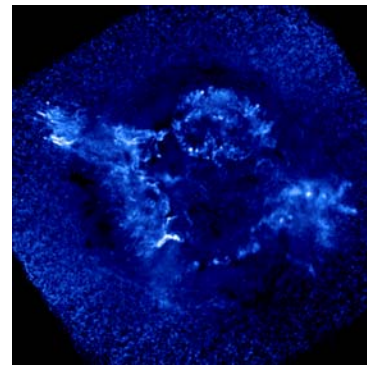


Cassiopeia A (Chandra)

One million seconds of x-ray image data were used to construct this view of supernova remnant [Cassiopeia A](#), the expanding debris cloud from a stellar explosion. Cas A's outer green ring, ~10 light-years in diameter, marks the location of the expanding shock from the original supernova explosion. In the upper left portion of the remnant, a structure extends beyond it, evidence that the initial explosion may have also produced energetic jets.

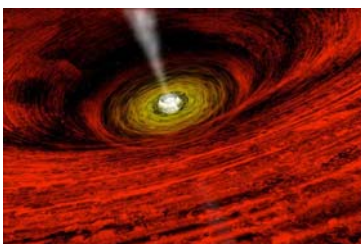
Still glowing in x-rays, the tiny point source near the center of Cas A is a neutron star, the collapsed remains of

the stellar core. In the blue-colored Cas A image specially processed to highlight silicon ions, a counter-jet can be seen on the lower right. The X-ray spectra show that the jet and counter-jet are rich in silicon atoms and relatively poor in iron atoms. This indicates that the jets formed soon after the initial explosion of the star; otherwise, the jets should have contained large quantities of iron from the star's central regions. The bright blue fingers located near the shock



Cassiopeia A (Chandra)

wave on the lower left are composed almost purely of iron gas. This iron was produced in the central, hottest regions of the star and somehow ejected in a direction almost perpendicular to the jets. The bright source at the center of the image is presumed to be a neutron star created during the supernova. Unlike the rapidly rotating neutron stars in other supernova remnants that are surrounded by dynamic magnetized clouds of electrons called pulsar wind nebulas, this neutron star is quiet, faint, and so far shows no evidence for pulsed radiation. One explanation could be that the explosion that created Cas A produced high-speed jets similar to but less energetic than the hypernova jets thought to produce gamma-ray bursts. During the explosion, the neutron star may have developed an extremely strong magnetic field that helped to accelerate the jets. This super-strong magnetic field later stifled any pulsar wind activity, so the neutron star today resembles other strong-field neutron stars in lacking a pulsar wind nebula; Cas A may contain a magnetar.

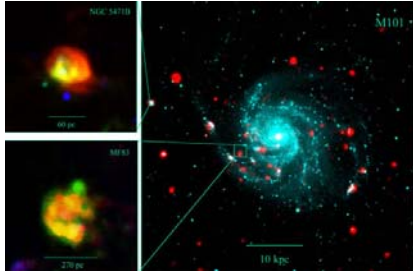


Black Hole (April Hobart, Chandra)

If the core remnant of a collapsed massive star exceeds 3 solar masses, neutron degeneracy pressure cannot stop the complete and total collapse of the star. The neutrons get pushed into each other until the star becomes a region, or boundary, in space around the black hole, called the event horizon, beyond which we cannot see. The extreme gravitational field within the event horizon emits no



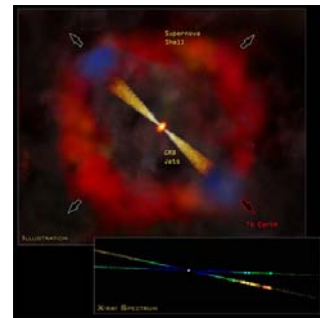
radiation; however, it can be indirectly detected by its effects on the spacetime around it - including accretion *Binary System (NASA artist)* disks and companion stars. Artist illustrations are usually used to portray these conditions, such as the [black hole](#) and [binary system](#) shown.



Hypernova in M100 (Hubble)

Gamma-ray bursts (GRBs) are among the most energetic and most luminous explosions in the Universe. They occur roughly once a day, last from a few thousandths of a second to a few hundred seconds, and come from all different directions of the sky. Their gamma radiation is more energetic than visible light and can be measured by satellites orbiting the Earth in space. The energy set free by the bursts in just one second is comparable to the energy production of the Sun during its whole life. There is evidence that GRBs are produced during catastrophic explosions which end the lives of extremely massive stars. Two possible candidates for this type of massive explosive event have been discovered in the spiral galaxy [M100](#). The gigantic energy which powers the gamma-ray burst is thought to be provided by rapidly spinning black holes which form when the central core of a very massive star becomes unstable and collapses under its own gravity. The infalling stellar material becomes part of the newly formed black hole, which releases enormous amounts of energy in two jets. The jets expand relativistically, at almost the speed of light, along the rotation axis. Before they break out from the stellar surface, they have to drill their way through thick layers of stellar material, thus getting collimated into very narrow beams with an opening angle of only a few degrees. Recent observations, like [GRB 020813](#), are confirming that the origin of long gamma-ray bursts comes from exploding massive stars.

second is comparable to the energy production of the Sun



GRB 020813 (Chandra)



Cygnus Region (CGPS)

Stellar evolution is a fascinating and fundamental topic. We are just beginning to construct the knowledge necessary to understand the processes of star formation and destruction. Ground-based and orbiting spacecraft are imaging stars in all stages of evolution from radio through gamma rays. Images, like the radio image of the [Cygnus region](#) shown here, give us fascinating views of stellar evolution - from protostars just emerging from their stellar cocoons to thermonuclear fusion in massive hot, blue stars, to supernovae remnants that result from the catastrophic collapses of stellar cores. Somehow, within this maelstrom of turbulence, intense radiation and ferocious stellar winds, stars and planetary systems form. Technological advances are allowing us to explore the universe in unprecedented detail, and with these dramatic improvements in resolution come the prospect of significant advances in understanding a wide range of cosmic phenomena, including the never-ending cycle of stellar formation and destruction.

