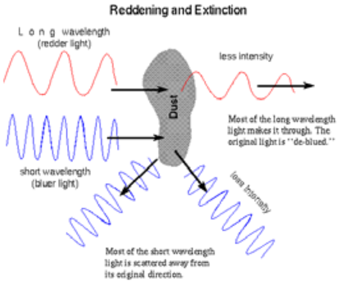
Stellar Evolution – Cosmic Cycles of Formation and Destruction

Interstellar Medium and Nebulas:

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 gases 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 created during the Big Bang, enriched with heavier elements from the nuclear fusion of elements in the cores of the following generations of stars. The interstellar medium is immersed in radiation from stars, magnetic fields, and cosmic ray particles, and has an average temperature of ~1,000,000 Kelvin (K).

The interstellar dust particles are extremely small – usually less than about one thousandth (1/1000th) of a millimeter across – and composed mostly of 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.



Nebulas are denser agglomerations of interstellar gas and dust; the main types of nebulas 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/cm^3. In the Tony Hallas image to the right is the emission nebula M42, located in the constellation of Orion. The hot luminous stars to within the nebula are ionizing the interstellar hydrogen, and protons and electrons are recombining and emitting red light.

M42 *(Tony Hallas)*

Witch Head Nebula (DSS)

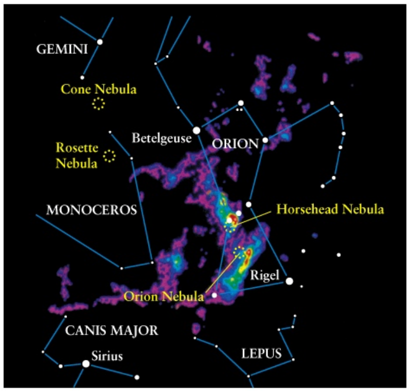
A nebula that is mainly composed of cool interstellar dust that reflects and scatters light from nearby stars is called a reflection nebula. They are usually blue because the scattering is more efficient for blue light by the dust particles. The Witch Head Nebula to the left is a reflection nebula, and is also glowing due to the ultraviolet radiation from the nearby hot, blue massive star Rigel in the constellation of Orion. Absorption nebulas are physically very similar to reflection nebulas; they look different only because of the geometry of the cloud of dust, the light source and Earth. Absorption, (dark) nebulas, 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 nebulas are often seen within the same field of view. The image of NGC 6559 below, a bright red emission nebula, also contains a large region of nebulosity surrounding the two hot young stars located in the lower left portion of the image. The image also contains dark clouds and filaments, highlighted against the bright emission nebula. Emission and reflection nebulas are often associated with star formation regions as they are caused by ultraviolet emissions from hot, young stars; however, stars do not form within these types of nebulas. Emission and reflection nebulas are too warm and diffuse to support star formation.

Horsehead Nebula (CFHT)

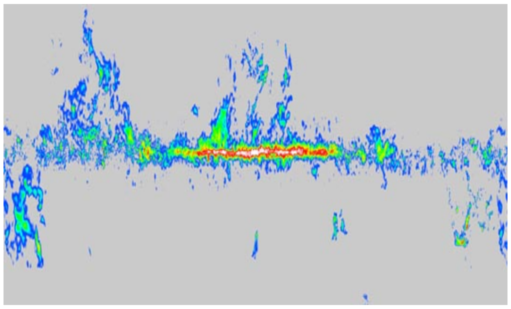
NGC 6559 (Adam Block, U Arizona)

Giant Molecular Clouds and Protostars:

Huge complexes of interstellar gas and dust left over from the formation of galaxies, 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/cm^3) 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 (LY) and contain enough gas to form from about 10 to 10,000,000 stars like our Sun. Molecular clouds that exceed the mass of ~100,000 suns are called Giant Molecular Clouds (GMC's). A typical spiral galaxy contains about 1,000 to 2,000 Giant Molecular Clouds and many smaller ones. These clouds were first discovered in our Milky Way Galaxy with radio telescopes about 30 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 location of the GMC in the region of Orion – produced by radio mapping of carbon monoxide (CO) gas.



Giant Molecular Cloud in Orion

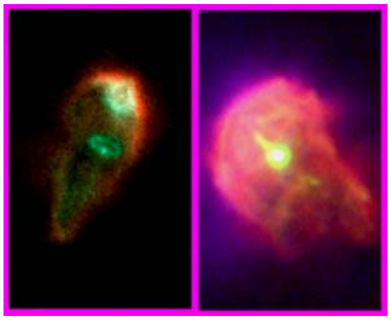


Milky Way Galaxy Molecular Map (CFA, Harvard)

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. Pertubations from spiral density waves within the spiral arm structure, collisions between nearby clouds, supernova 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, ESA)

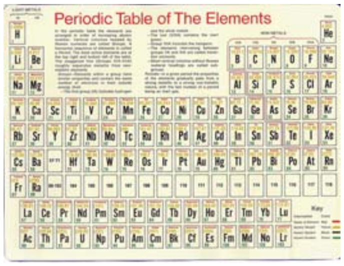
As a gas core collapses it heats up due to friction as the gas particles bump into each other. The energy the gas particles had from falling under the force of gravity (gravitational potential) gets converted to heat (thermal) energy. The gas cores become warm enough to produce infrared and microwave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



Protoplanetary Disks (Hubble)

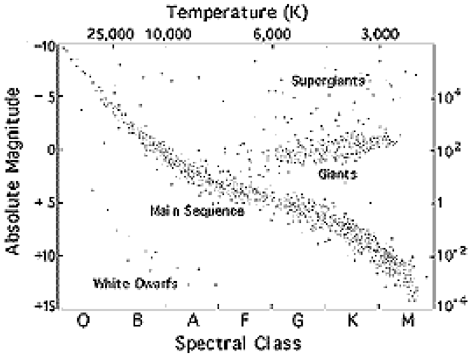
Introduction to the H-R Diagram:

The evolutionary sequences for stars are described by their position on a graph 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.



The Periodic Table of the Elements

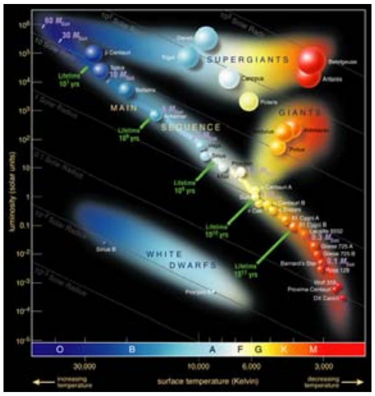
The periodic table of the elements is an arrangement of all the known elements in order of increasing atomic number. The reason why the elements are arranged as they are in the periodic table is to fit them all, with their widely diverse physical and chemical properties, into a logical pattern. The vertical 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 shows the periodicity and trends of some properties, such as electron configuration, metalicity, atomic radii, and melting points. The location of any individual element in the table determines the characteristics and properties of that element, as well as what types of chemical bonds it forms and chemical reactions it will undergo.



The Hertzsprung-Russell (H-R) Diagram

The Hertzsprung-Russell diagram, or H-R diagram, is the periodic table of the stars – an analog of the periodic table of the elements. 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. Unlike the periodic table however, the physical characteristics of stars change over time, and therefore their positions on the H-R diagram change also – so the H-R diagram can 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 are 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 (ZAMS) star. 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, the Sun 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 with hydrogen to helium fusion occurring within their cores, occupy the same position on the main sequence as the Sun; they stay in that location, with that specific relationship of temperature and absolute magnitude, until the hydrogen within the core becomes depleted and the fusion of hydrogen nuclei to helium nuclei stops. The mass-luminosity relationship for main sequence stars is defined as: L/L (Sun) ~ $[M/M\ (\text{Sun})]^4$. 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(years) = 10^{10}M/L. (See H-R diagram below)



Some Stars Plotted on the H-R Diagram

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. The core hydrogen has been converted to helium; however, there is still hydrogen in the outer layers surrounding the helium core of the star. 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 stars 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 periodicity of ~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 between mass and luminosity for stars on the giant or any other branch of the H-R diagram – only the main sequence.

The Supergiant Branch: Stars greater than ~8 solar masses evolve horizontally 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. They begin as spectral types O and B (white and blue in color) on the main sequence and evolve to class M (red), 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 stage and pulsate with a period of 1 - 70 days). Eventually massive stars reach the supergiant branch and undergo a core collapse in a Type II supernova event, leaving behind a pulsar, neutron star, magnetar or black hole and a supernova remnant. Some hyper-massive stars collapse into back holes without a supernova event, and some undergo a supernova event that leaves no core remnant behind – such as SN2006GY.

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.

NOTE: This is only a brief introduction to stellar evolution on the H-R diagram. There are exceptions to some of the evolutionary sequences, and the associated masses are “ballpark” numbers only. There are more stellar classifications than the ones mentioned above. A more in-depth description of the evolutionary tracks of stars across the H-R diagram – especially the transition stages involving variable stars – is located at:
http://chandra.harvard.edu/edu/formal/variable_stars/bg_info.html

Young Stellar Objects:


HH Objects (Adam Block, U Arizona)

Any star that has evolved past the protostar stage (i.e. is producing energy due to 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 (HH) objects, T Tauri stars, and, in general, immature stars prone to irregular brightening, embedded in nebulosity, and associated with bipolar outflows. Observations of Herbig-Haro objects provide a dramatically clear look at collapsing circumstellar disks of dust and gas that build stars and provide the ingredients for planetary systems. Jets of hot gas are funneled from deep within these embryonic systems, and bursts of material are ejected from the young stellar objects at speeds of nearly a half-million kilometers per hour. The Herbig-Haro object HH111 shows the fast-moving jet 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)

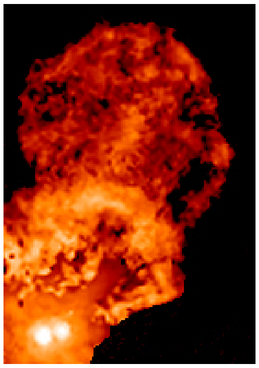

Trifid Nebula (Hubble)

The Trifid Nebula is one of the most prominent nebulas 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 stellar object at its tip are apparent in the image. The stellar jet is emerging from the wall of a cloud

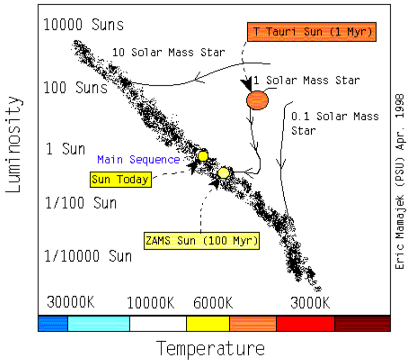
EGG (Hubble)

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", points back 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 nebulas 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: classical 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 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 the main sequence for mid-mass sized stars and are located just above the main sequence on the H-R diagram.



***XZ Tauri* (Hubble)**



Brown Dwarfs & Low Mass Stars:

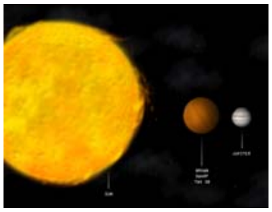
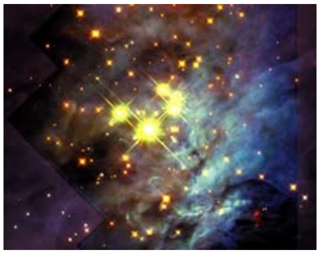
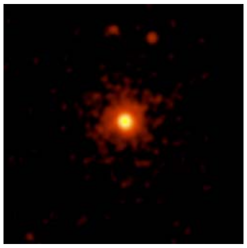


Illustration (Chandra)

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. Because core temperature rises with gravitational pressure, the star must have a minimum mass: about 75 times the mass of the planet Jupiter, or approximately 8 percent of the mass of the Sun. A brown dwarf does not have enough mass; 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 eventual radiate all their heat into space. The composite Hubble image shows the bright Trapezium stars (optical) within the Orion Nebula combined with an infrared image that shows a swarm of brown dwarfs.


Brown Dwarfs in Orion (Hubble)

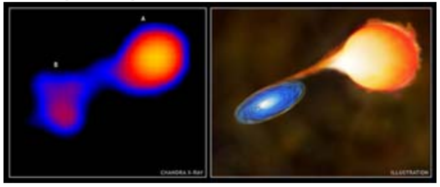

Proxima Centauri (Chandra)

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 further 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)

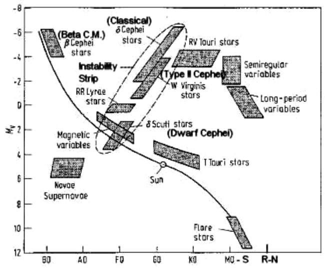
Thermonuclear fusion in stars with masses between ~0.8 and 8 solar masses, similar to our Sun, produces the outward radiation pressure to counterbalance gravitational forces for approximately ten billion years. When all the core hydrogen nuclei have been converted to helium nuclei and fusion stops, gravity 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 core temperature becomes high enough for helium nuclei to fuse into carbon and oxygen nuclei, with hydrogen to helium fusion continuing 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.



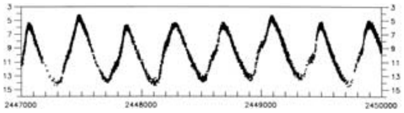
Mira A (red giant) and Mira B (white dwarf)

Chandra Image and Illustration

During this pulsating stage the star is called a Mira 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 – as shown on the H-R diagram to the right.



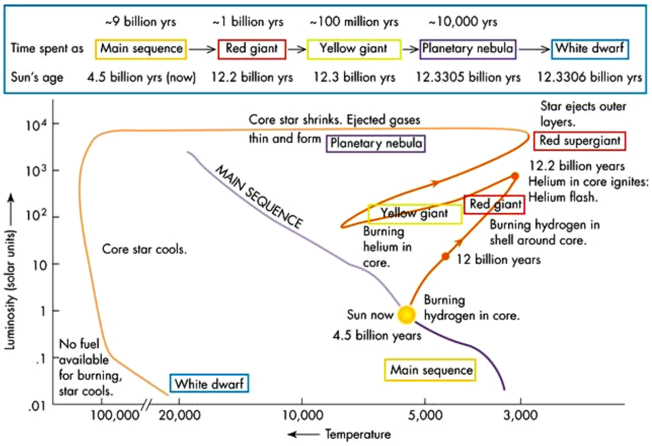
H-R Diagram



Mira Light Curve (AAVSO)

The Helix Nebula (La Silla Obs)

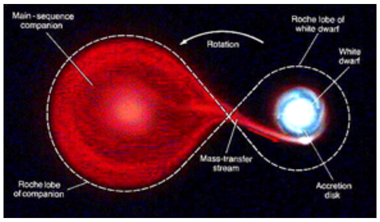
Eventually, the material ejected by the star forms an envelope of gas called a planetary nebula which expands into the surrounding interstellar medium at ~17-35 km/hr. The core of the star left in the center of the planetary nebula is called a white dwarf. The planetary nebula is very tenuous, and becomes so thin that after ~50,000 years it is no longer visible - therefore all planetary nebulas are very young. The white dwarf can not create internal pressure and its complete collapse is prevented by quantum mechanics. Two electrons with the same "spin" are not allowed to occupy the same energy level. Since there are only two ways an electron can spin, only two electrons can occupy any single energy level; this is known as the Pauli Exclusion Principle. In a normal gas, this is not a problem; there are not enough electrons floating around to completely fill up all the energy levels. In a white dwarf, all of the electrons are forced close together, and all the energy levels in its atoms are filled up with electrons. Since all the energy levels are filled, and it is impossible to put more than two electrons in each level, the white dwarf is now composed of "degenerate" matter. Because a white dwarf is degenerate, gravity cannot compress it any more because quantum mechanics tells us there is no more available space. The complete collapse of the white dwarf is prevented because it is held in equilibrium with gravity by electron degeneracy pressure. The white dwarf is extremely dense, ~200,000 times more dense than the Earth. 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. Over hundreds of billions to a trillion years the white dwarf will radiate its remaining energy away and become a black dwarf - a cold, dark mass of electron degenerate matter.



This H-R diagram the shows the evolutionary track of the Sun, which is halfway through its lifetime of ~10 billion years on the main sequence. It is a spectral type G2 star, has an effective surface temperature of ~5800K, 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, ~3000K, reddish in color, and more luminous – in excess of 500 solar luminosities. After ~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.

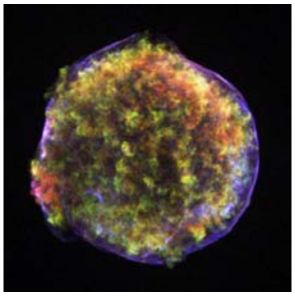
During the final core collapse the core exceeds its equilibrium point and rebounds, throwing off its outer atmospheric layers into a planetary nebula. The remaining carbon core – the white dwarf – will then reside on the white dwarf branch of the H-R diagram. The white dwarf is very dim and very hot – with a temperature of ~20,000K.

Mira Red Giant with White Dwarf Companion (Chandra)



Contact Binary Red Giant & White Dwarf

However, a white dwarf is not always the end product in the collapse of a mid-sized (~.8 - 8 solar masses) star if it is in a contact 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 core hydrogen faster than its less massive companion, transitions to a red giant, shrugs off a planetary nebula, and collapses into a white dwarf. Eventually the companion star runs out of core hydrogen and enters 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 outer layers of 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. Magnetic friction slows the matter's orbital motion, which causes the material to spiral through the disk to the surface of the white dwarf. The falling and spiraling of the matter towards the white dwarf releases large amounts of gravitational energy and heats the accretion disk. The white dwarf accretes matter from its companion relatively rapidly at the Langrangian point - the point where the Roche lobe of the white dwarf and red giant make contact. The Roche lobe is the region of space around a star in a binary system within which orbiting material is gravitationally bound to that star; the red giant's outer atmospheric layers are easily transferred by the strong gravitational field of the white dwarf.



Tycho's SNR (Chandra)

Consequently, the white dwarf increases in mass. When mass accretion of the white dwarf approaches the Chandrasekhar Limit 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 moves from the center to the surface and the white dwarf undergoes a thermonuclear explosion and is completely destroyed. Only the remnant remains. All of the core's matter - the products of nuclear fusion (iron, nickel, silicon, magnesium, and nickel, silicon, magnesium, and other heavy elements) plus unfused carbon and oxygen - are ejected into the interstellar medium (ISM) at speeds upwards of ~48,000,000 km/hr. This type of event is called a Type Ia supernova – the thermonuclear destruction of a white dwarf.

Massive Stars:

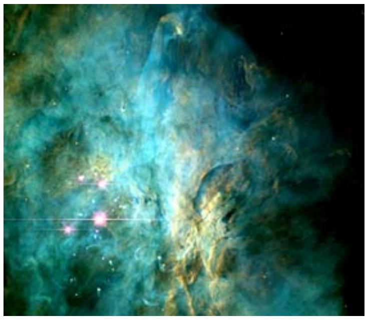
M7 Open Cluster in Scorpius (NOAO)

Massive star formation often occurs in groups – such as 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 not even exist for the most massive stars.

Eagle Nebula Star Formation Region (NOAO)

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 supernova explosions. Most stars form in the neighborhood of a massive star, so they influence the rate of low-mass star formation. Star formation will stop after a relatively small number of stars have formed within a star formation region. That's because the stellar nursery is radiated 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. When the temperature exceeds about 1900 K, the gas molecules break down into atoms, 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. The Eagle Nebula region above contains beautiful and intricately shaped areas carved out by the radiation from hot young massive stars.

Orion Nebula (Nicolas Villegas)



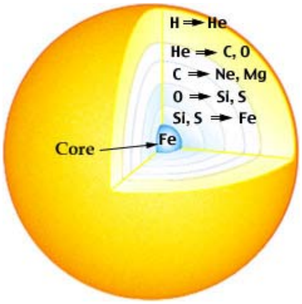
Trapezium in Orion (Hubble)

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

Hodge 301 (Hubble)



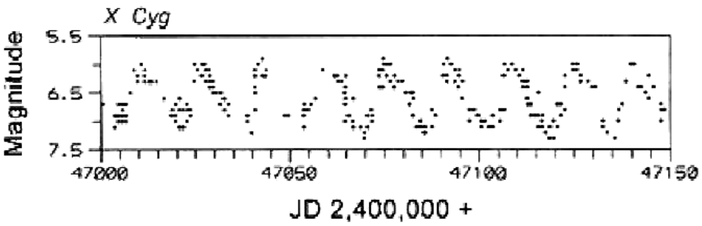
The star's structure now resembles an onion. The central core of the onion consists of iron nuclei. Surrounding the core is a shell in which silicon and sulfur are fusing, adding more iron nuclei to the iron core. In additional levels further out, lighter elements fuse - oxygen, carbon, helium, and hydrogen. 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 expulsion 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, these massive stars leave the main sequence of the H-R diagram and start evolving towards the supergiant 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

Rosette Nebula Massive Star Formation

(Chandra & Hubble)

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. The star 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 transition to the red supergiant branch.

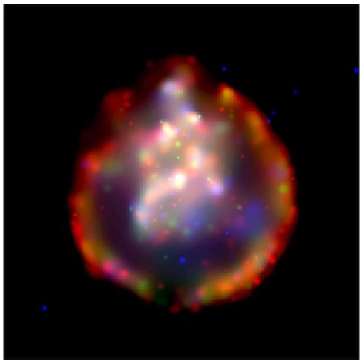
Cepheids have a repeating cycle of change that is periodic - as regular as the beating of a heart. Observations of the changes in apparent magnitude of variable stars - including Cepheids - are plotted as the apparent magnitude versus time, usually in Julian Date (JD). The resulting graph is called a 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 (dimmest), and back to maximum magnitude (brightness.)



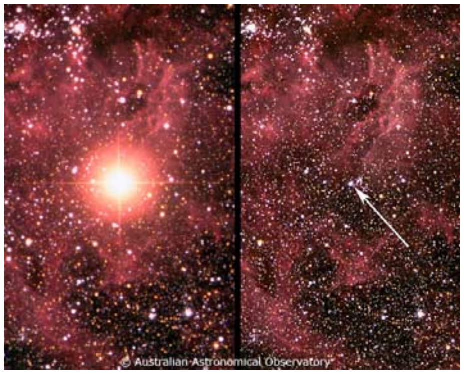
[http://www.aavso.org/types-variables]

Eta Carinae (Chandra & Hubble)

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 no longer able to stop the 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. The hypermassive star Eta Carinae is expected to collapse within the next 100,000 years. The supernova Remnant SNR 0103-72.6 occurred ~10,000 years ago 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 Galaxy these objects are obscured by the gas and dust within the spiral arms.



SNR 0103-72.6 (Chandra)

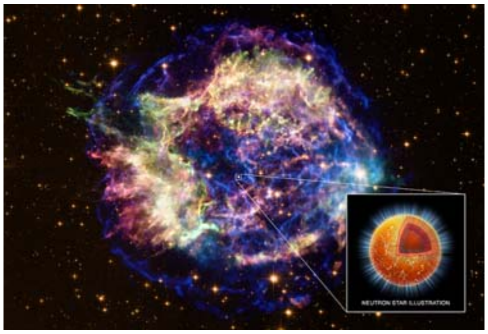


SN 1987A (AAO)

Veil Nebula (NOAO)

Cassiopeia A (CAS A) SNR (Hubble)

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 to the star's surface. The shock wave heats the outer layers, inducing explosive nuclear fusion, and ejects the outermost layers in excess of speeds of ~16 million kilometers per hour. The energy released by the shockwave creates 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 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 core end product left behind depends upon the initial mass of the star, and is either a neutron star, pulsar, magnetar, or black hole.

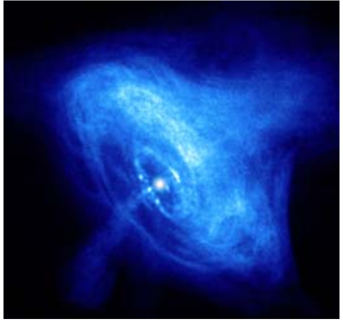


Cas A SNR Composite Image & Illustration

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 of more than 1.4 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 Cas A contains a a neutron star. Ten years of observations with Chandra have revealed a 4% decline in the temperature of this neutron star, an unexpectedly rapid cooling. Research shows that this cooling is likely caused by a neutron superfluid forming in its central regions, the first direct evidence for this bizarre state of matter in the core of a neutron star. Superfluid is a state of matter which behaves like a fluid with zero viscosity. The inset shows an artist's impression of the neutron star at the center of Cas A. The different colored layers in the cutout region show the crust (orange), the core (red), where densities are much higher, and the part of the core where the neutrons are thought to be in a superfluid state (inner red ball). The blue rays emanating from the center of the star represent the copious numbers of neutrinos -- nearly massless, weakly interacting particles -- that are created as the core temperature falls below a critical level and a neutron superfluid is formed. These neutrinos escape from the star, taking energy with them and causing the star to cool much more rapidly. Neutron degeneracy pressure maintains equilibrium with gravity for a core of no more than approximately 2.4 - 3 stellar masses.


The Crab Nebula (Hubble & 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 crab nebula – a Type II supernova event – 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 filed to produce high-energy emissions such as X-rays and gamma-ray. The pulses of radiation match the rate of the rotation of the neutron star.


The Crab Pulsar Movie (Chandra)

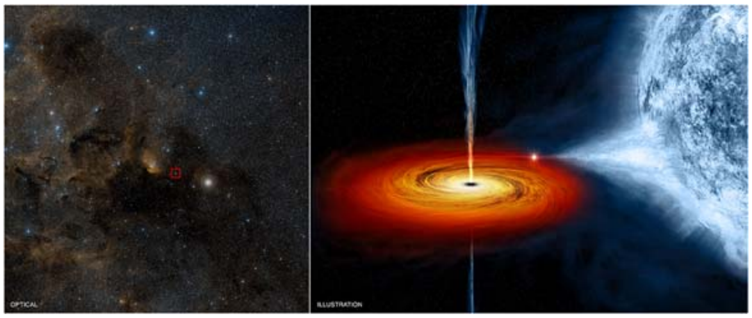
Magnetars are neutron stars that have super strong magnetic fields, ~ 100 trillion times as strong as the Earth's magnetic field. These fields are so intense that the solid neutron star crust buckles and shifts under its influence. The resulting star quakes could repeatedly generate brief flashes of hard X-rays and soft gamma-rays - giving rise to the rare but 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, contains a magnetar which is now recognized as a soft gamma-ray repeater.


Magnetar Illustration (Chandra)


N49 (Hubble & Chandra)

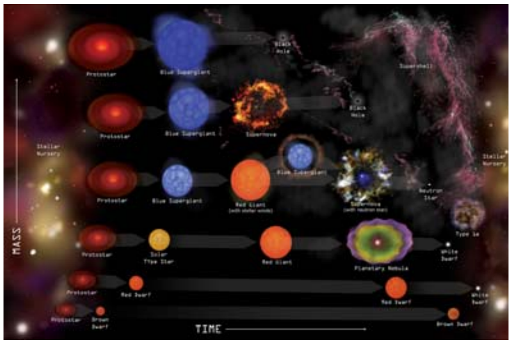
M33 X-7 X-Ray Binary (Chandra)

If the core remnant of a collapsed massive star exceeds ~2.4-3 solar masses, neutron degeneracy pressure cannot stop the complete and total collapse of the star. The neutrons get pushed into each other until the stellar core becomes a region with such extreme gravity and spacetime becomes so distorted that it becomes a black hole. At the center of the black hole is a region described as a gravitational singularity – a region where the spacetime curvature becomes infinite. The singularity is considered to have zero volume, and as it contains ~95% of the original stellar material, it is also considered to have infinite density. The singularity has a spherical boundary called the photon sphere which terminates at its outer surface at the event horizon. The extreme gravitational field within the event horizon emits no radiation as the escape velocity exceeds the speed of light. Black holes can be indirectly detected by their effect on the surrounding spacetime - including accretion disks and companion stars. Most stars are in binary or multiple star systems. The most massive stars in these systems spend the least amount of time on the main sequence before evolving into their final end products – usually supernova remnants and stellar mass black holes. Binary systems that include black holes are categorized as X-ray binaries because radiation from the system is strong in X-rays. The X-ray binary system M33 X-7 shown above consists of a 16 solar mass black hole orbiting a 70 solar mass companion. The black hole is surrounded by an accretion disk of material fed by wind from the blue companion star, which has been swept into orbit around the black hole. Rather than flowing unimpeded and uniformly into space, wind from the star is pulled towards the black hole by its powerful gravity. The wind that does make it past the black hole is disrupted, causing turbulence and ripples beyond the disk. The companion star itself is also distorted by the gravity from the black hole. The star is stretched slightly in the direction of the black hole, causing it to become less dense in this region and to appear darker.



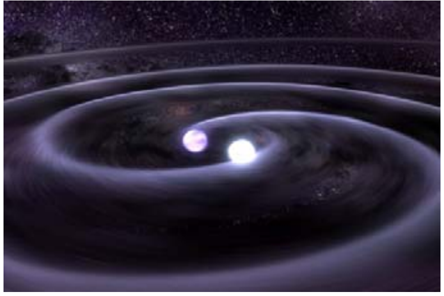
Star Formation Region in Cygnus (DSS) and Artist Illustration of Cygnus X-1

Cygnus X-1 is located near large active regions of star formation in the Milky Way, as seen in the optical image to the right that spans ~700 light years across. The artist's illustration next to the image depicts what astronomers think might be happening within the Cygnus X-1 system. Cygnus X-1 is a 15 stellar mass black hole formed from the collapse of a massive star in a Type II supernova event. The black hole accretes material from its massive, blue companion star and the material forms a disk that rotates around the black hole before falling into it or being redirected away from the black hole in the form of powerful jets perpendicular to the spin axis of Cygnus X-1. The system is ~6070 light years from Earth and formed ~6 million years ago.



Stellar Evolution: A Journey with Chandra Interactive Poster

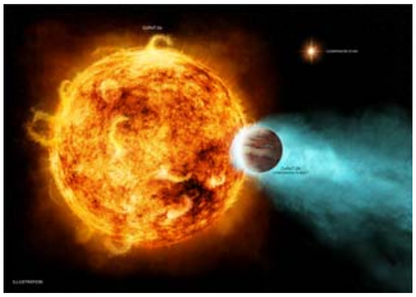
This has been a brief introduction to stellar evolution – the process during which stars undergo a sequence of radical changes from formation to destruction and final end products. Stellar evolution is a complex process and not well understood. The sequences presented for low, mid-sized and massive stars are not the only evolutionary sequences – and some of the end products can be formed during different circumstances. For example, the core collapse of a massive star is not the only process that can produce a neutron star. Two white dwarfs in a binary system can coalesce into a neutron star if the total mass does not exceed 2.4 solar masses. RX J0806.3+1527 (or J0806) is a binary star system comprised of two white dwarfs orbiting each other ~every 5 minutes. The orbital system is decreasing by 1.2 milliseconds/year and therefore moving closer to each other by .61 meters/day. If the total mass of the two white dwarfs exceeded 2.4 solar masses – the limit at which neutron degeneracy pressure can hold a stellar core in equilibrium with gravity – the end result would be a Type Ia supernova event. If the combined mass exceeded 1.4 solar masses, but less than 2.4 solar masses, they would coalesce into a neutron star. However, it is estimated that the J0806 system white dwarfs are each approximately 0.5 solar masses – in which case they would coalesce into a larger white dwarf.



RX J0806.3+1527 Movie (Chandra)

The Tarantula Nebula (John P Gleason)

Scientists are just beginning to construct the knowledge necessary to understand the complexities of stellar evolution. Ground-based and orbiting spacecraft are imaging stars in all stages of evolution with the entire electromagnetic spectrum – radio through gamma rays. Images, like the image of the Tarantula Nebula shown here, give us extraordinary 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 catastrophic collapses or thermonuclear explosions that create the elements for the next generation of protostars and stars. Somehow, within this maelstrom of turbulence, intense radiation and ferocious stellar winds, stars and planetary systems – and even life - form. Technological advances are allowing us to explore the universe in unprecedented detail, and each observation brings new knowledge and discoveries, i.e. Earth was the only known planet until 1991 – and as of June, 2012, 778 planets have been identified.



CoRoT-2A Star and Planet (Chandra)