Stellar evolution

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The large-scale, systematic, and irreversible changes over time of the structure and composition of a star.

Types of stars

Dozens of different types of stars populate the Milky Way Galaxy. The most common are main-sequence dwarfs like the Sun that fuse hydrogen into helium within their cores (the core of the Sun occupies about half its mass). Dwarfs run the full gamut of stellar masses, from perhaps as much as 200 solar masses (200 $M_\odot$) down to the minimum of 0.075 solar mass (beneath which the full proton-proton chain does not operate). They occupy the spectral sequence from class O (maximum effective temperature nearly 50,000 K or 90,000°F, maximum luminosity 5×10^6 solar), through classes B, A, F, G, K, and M, to the new class L (2400 K or 3860°F and under, typical luminosity below 10^{-4} solar). Within the main sequence, they break into two broad groups, those under 1.3 solar masses (class F5), whose luminosities derive from the proton-proton chain, and higher-mass stars that are supported principally by the carbon cycle. Below the end of the main sequence (masses less than 0.075 $M_\odot$) lie the brown dwarfs that occupy half of class L and all of class T (the latter under 1400 K or 2060°F). These shine both from gravitational energy and from fusion of their natural deuterium. Their low-mass limit is unknown. *See also:* CARBON-NITROGEN-OXYGEN CYCLES; PROTON-PROTON CHAIN; SPECTRAL TYPE; STAR.

Scattered among the dwarfs are different kinds of stars that are distinguishable (through comparison with the dwarfs) by their sizes and luminosities: luminous giants (with maximum radii equaling that of the inner solar system), brilliant supergiants (maximum radii comparable to the orbits of Jupiter and Saturn), subgiants (which fall between giants and dwarfs), and dim white dwarfs (the size of Earth). All these classifications may be broken into subclasses. The list also includes the central stars of planetary nebulae, double stars, novae, supernovae, neutron stars, and black holes. The study of stellar evolution seeks to determine where they all came from. Do they stand alone, or are they somehow connected? If the latter, what kinds of stars precede and succeed what other kinds?

Stellar models

Stars age so slowly that it is impossible—except under rare circumstances—to see the transformations take place. Instead, stellar theorists, using the laws of physics, build numerical models of stars and then age them. The procedure is simple in principle, but difficult in practice. At the start, a star is in hydrostatic equilibrium, in which each layer supports the layers above it (with the pressure difference across a layer equaling the weight of the layer) and is internally supported by thermonuclear fusion. The relation between pressure, density, and temperature is given by the perfect gas law, $P = NkT$, where P is pressure, N is the number density of atomic particles, k is Boltzmann's constant, and T is temperature. Other equations involve the mass within a given radius, the rate at which energy is generated at a given radius, and the temperature gradient, which controls convection. As fusion proceeds and the rate of energy generation and the internal chemical composition change, the structure of the star changes as well. Stepwise calculations that predict luminosity, radius, and effective temperature then allow the star to be followed as it "moves" (changes in effective temperature and luminosity) on the Hertzsprung-Russell (HR) diagram. When appropriate mass loss is taken into account, most of the different kinds of stars fall into place. *See also:* GAS; HERTZSPRUNG-RUSSELL DIAGRAM; HYDROSTATICS; THERMODYNAMIC PROCESSES.

Star formation

Stars are born from compact knots within dark molecular clouds that are refrigerated by dust that blocks heating starlight (**Fig. 1**). If the random knots, compressed by supernovae or other means, are dense enough, they can contract under their own gravity. Conservation of angular momentum demands that as they collapse, they must spin faster. Star formation therefore requires that angular momentum be removed so that the new "young stellar objects" do not completely tear themselves apart before they can become fully developing protostars. *See also:* ANGULAR MOMENTUM; MOLECULAR CLOUD.

High-speed particles (cosmic rays) from exploding stars partially ionize the dusty knots. The ions grab onto the weak magnetic field of the Galaxy and, as a result of their physical interaction with neutral atoms and molecules, provide the initial means to slow the rotation. If the rotation is still too fast, the contracting body may split into a double (or more complex) star, although the origins of doubles have not been clearly determined. Indeed, a contracting protostar still rotates progressively faster until the part of its mass that has not accreted to the star itself is spun out into a dusty disk, from which planets might later accumulate. From the disk shoot powerful molecular flows that slow the star still more, aiding in its formation (**Fig. 2**). *See also:* PROTOSTAR.

When the protostar's interior reaches about 10^6 K (1.8×10^6°F), it can fuse its internal deuterium. That and convection, which brings in fresh deuterium from outside the nuclear-burning zone, bring some stability, and a star can now be said to have been born. Stars like the Sun shrink at constant temperature until deuterium fusion dies down. Then they heat at roughly constant luminosity until the full proton-proton chain begins, which provides the stars' luminosity and support and stops the contraction. The stars then settle onto the zero-age main sequence (from which they will later evolve). At the same time, the surrounding dusty cloud is clearing, allowing new, accreting, and highly active T Tauri stars to be seen flocking around their birthclouds (**Fig. 3**). The whole process takes only 10 or so million years, with the mature stars then leaving their birthplaces, destined both to age and to orbit the Galaxy. High-mass stars proceed similarly, but at such a great pace that the death process begins even as the birth process is ending. *See also:* T TAURI STAR.

Fig. 1 Mosaic of the Orion Nebula assembled from the *Hubble Space Telescope*'s Advanced Camera for Surveys in one of the most detailed astronomical images ever produced. The nebula is a gas cloud excited to incandescence by hot young stars in its interior, at the edge of an immense molecular cloud. At 1500 light-years, it is the nearest large star-forming region, and its energetic stars have blown away obscuring gas and dust. A range of star-formation stages is observed, from massive, young stars that are shaping the nebula to pillars of dense gas that may be the homes of budding stars. (*NASA; ESA; M. Robberto, Space Telescope Science Institute/ESA; Hubble Space Telescope Orion Treasury Project Team*)

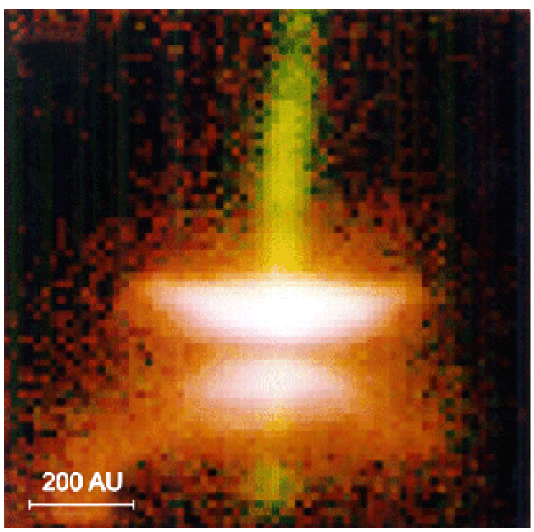

Fig. 2 Focused, even created, by a circumstellar disk, a jet pours from the youthful star Herbig-Haro 30 (HH 30). (*C. Burrows, Space Telescope Science Institute; WPFC2 Science Team; NASA*)

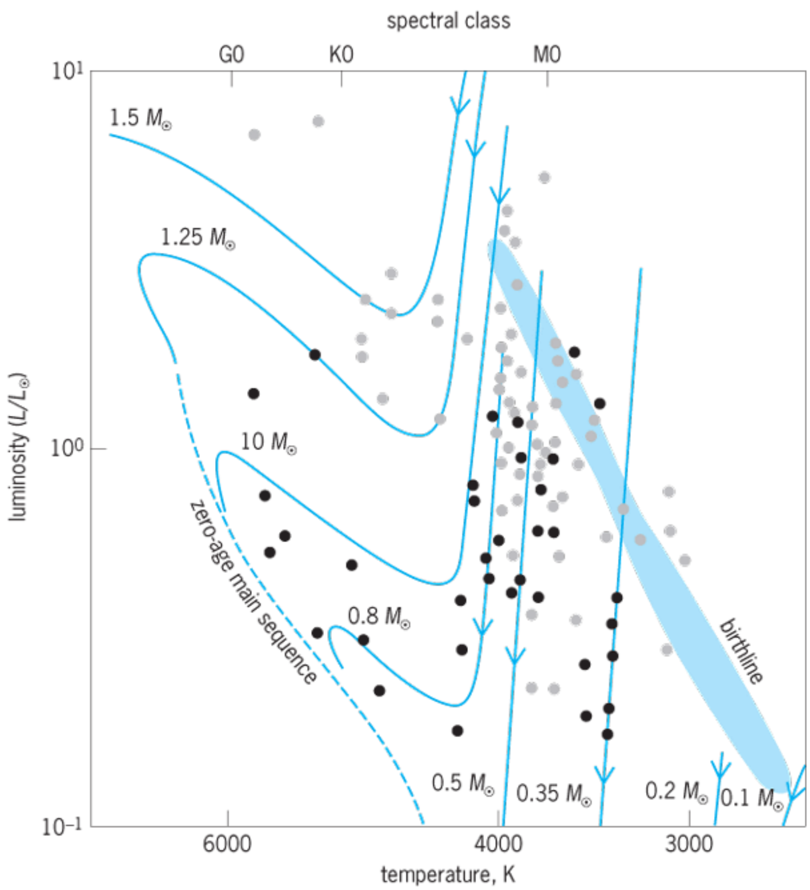

Fig. 3 **Hertzsprung-Russell diagram of star formation. Stars begin to stabilize at the birthline and then descend on evolutionary tracks as T Tauri stars (dots) toward the zero-age main sequence. (*After J. B. Kaler, Cosmic Clouds, W. H. Freeman, New York, 1997, from work of S. W. Stahler and I. Iben, Jr.*)**

Early evolution

The main sequence is that zone on the HR diagram in which stars are stabilized against gravitational contraction by fusion. The higher the stellar mass, the greater the internal compression and temperature, and the more luminous the star. Hydrogen fusion is highly sensitive to temperature, with a small increase in stellar mass meaning a much higher fusion rate. Although greater mass means a greater nuclear-burning core mass and therefore a larger fuel supply, the increased fusion rate more than offsets this and thereby shortens stellar life. A star's fuel supply is proportional to its mass (M), while the rate of fusion is expressible by the luminosity (L). The average mass-luminosity relation found from binary stars is $L \propto M^{\Lambda.\Pi}$. If a star's lifetime t is proportional to (fuel supply)/(rate of use), then $t \propto M \,/\, L \propto M \,/\, M^{\Lambda.\Pi} = 1 \,/\, M^{\Theta.\Pi}$. While the new Sun was destined to survive on the main sequence for 10^{10} years, a 0.1-solar-mass star will live there for 10^{13} years, while a 100-solar-mass star will exhaust its core hydrogen in only 2.5×10^6 years.

Main-sequence life, while stable, is not altogether quiet. Even there, stars change and evolve. As hydrogen "burns" to helium, four particles (protons) are converted to one (a helium nucleus). The pressure of a gas depends on the number of particles per unit volume, not on their kind. The result is a slow shrinkage of the core, which increases the temperature, raises the fusion rate, and causes the core to eat into the surrounding hydrogen envelope (incorporating fresh fuel). As a result, main-sequence dwarfs slowly brighten and eventually expand and cool some at their surfaces. (The Sun will more than double in brightness, dooming life on Earth, long before its core hydrogen is gone.) As a result, the main sequence spreads itself into a band toward the cool side (to the right) of the zero-age main sequence, with the band widening toward the top.

Clusters of stars are born together in both space and time, most of them (presumably) with fully intact main sequences. As a cluster ages, stars peel off the main sequence (to become giants and supergiants) from the top down. A star cluster can be dated by where its main sequence ends. Open clusters, which occupy the Galaxy's disk, range from just forming to about 10^{10} years old, which gives the disk's age. The globular clusters of the Galaxy's halo, however, have burned their main sequences down to around 0.8 solar. This process takes roughly 12×10^9 years, which must be close to the age of the Galaxy. *See also:* MILKY WAY GALAXY; STAR CLUSTERS.

The main sequence is divided into three parts. Below 0.8 or 0.9 solar mass (roughly class G8), no star has ever had time to evolve. Low-mass (K and M dwarf) evolution is therefore of only academic interest. Stellar evolution deals with less than 15% of the stars. Their fates depend again on mass. Between 0.8 solar mass and around 9 solar masses (classes G8 to B1), the stars die as white dwarfs. Above this range (classes O and B0), they explode. Binary stars, whose origins are still unclear, contribute further to the richness of stellar phenomena.

Intermediate-mass evolution

Main-sequence life lasts until the core hydrogen is almost gone, at which time hydrogen fusion shuts down rather suddenly. With no support, the now-quiet helium core can contract more rapidly under gravity's force. It heats, causing hydrogen fusion to spread into a thick, enclosing shell that runs on the carbon cycle. With a new (though temporary) energy source, the star first dims somewhat while it expands and cools at the surface, changing its spectrum to class K. The transition takes only a few hundred million years or less, leaving few stars in the middle of the HR diagram, with those with lower masses appearing as F, G, and K subgiants.

The consequences again depend on mass. As core contraction proceeds beyond the rightward transition in the HR diagram, stars from about 1 to 5 solar masses (still fusing hydrogen in a shell) suddenly and dramatically increase their luminosities. The future Sun will eventually grow 1000 times brighter than it is today, and a 5-solar-mass star (which begins at about 600 solar luminosities) will reach nearly 3000 solar. At the same time, the stars swell to become red giants. While the core (roughly half a solar mass) of the future Sun shrinks to the size of Earth, the radius will expand to that of Mercury's orbit, or even beyond. When the core temperature climbs to 10^8 K, helium nuclei (alpha particles) begin fusing to unstable beryllium (^{8}Be), which quickly decays back to alpha particles, setting up an equilibrium. The tiny amount of ^{8}Be present reacts with additional alpha particles to

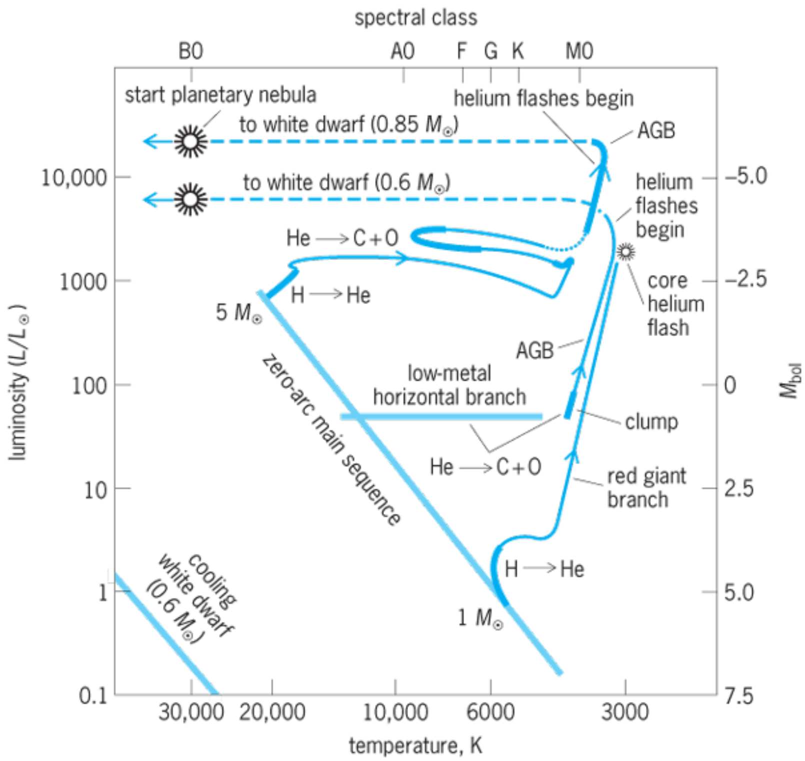

Fig. 4 **Hertzsprung-Russell diagram of evolution of intermediate-mass stars. These stars evolve from the main sequence to become giants that stabilize during helium fusion in a "clump." When helium fusion is done, they brighten again as AGB stars, lose their envelopes, and evolve to the left to produce planetary nebulae, finally, at lower left, becoming white dwarfs. (*After J. B. Kaler, Stars, New York, W. H. Freeman, 1992, 1993, from work of I. Iben, Jr.*)**

create carbon via the triple alpha process:

$$^{4}\mathrm{He} + {}^{4}\mathrm{He} \leftrightarrow {}^{8}\mathrm{Be}$$

$$^{8}\mathrm{Be} + {}^{4}\mathrm{He} \rightarrow {}^{12}\mathrm{C} + \text{gamma ray}$$

(The "skip" over lithium, beryllium, and boron renders these elements rare.) The initiation of the triple-alpha process is explosive in stars like the Sun, since the core electrons become degenerate, like those that support white dwarfs. (The sudden burst of energy is absorbed and does not reach the stellar surface.) Fusion with additional helium nuclei creates oxygen and even neon. Above 2 solar masses, helium burning starts more quietly (**Fig. 4**). *See also:* NUCLEOSYNTHESIS.

The star, now stabilized by a helium-burning core that is surrounded by a hydrogen-fusing shell, retreats about halfway down the red giant branch. The numerous lower-mass stars reside in the class K “red giant clump.” Low-mass metal-deficient globular cluster stars that have suffered different rates of mass loss spread out from the clump toward higher temperatures to create the distinctive horizontal branch. Energy-generating fusion reactions will try to proceed toward iron (the most stable of all nuclei). Some 80% of the energy is generated in hydrogen burning, so (discounting other burning modes) the helium-burning stage lasts only around 20% of the main-sequence lifetime. From 5 solar masses up, evolution proceeds similarly, but instead of settling into a distinct location on the HR diagram, the stars loop to the blue (higher temperatures), where they fuse helium as class G, F, and A giants. This change in evolutionary style is not abrupt, but gradual with increasing mass. *See also:* GIANT STAR.

Asymptotic giant branch (AGB)

When the helium has fused to carbon and oxygen, the core again contracts. Helium fusion spreads outward into a shell, and for the second time the star climbs the HR diagram’s giant branch. Since the second climb is roughly asymptotic to the first, the second climb creates the asymptotic giant branch. The shrinking carbon-oxygen core is now surrounded by a shell of fusing helium, while the old hydrogen-fusing shell expands, cools, and shuts down. Eventually, however, the helium shell runs out of fuel, and the hydrogen shell reignites. Hydrogen burning feeds fresh helium into the space between it and the carbon core, and when there is enough of it, helium burning reignites explosively in a helium flash (or thermal pulse) that can affect the star’s surface. The flash squelches hydrogen fusion, and the whole process starts again, with helium flashes coming at progressively shorter intervals. AGB stars become larger and brighter than before, passing into the cool end of class M, where they eventually become unstable enough to pulsate as long-period variables (Miras). The Sun will become 5000 times brighter than now and will reach out to the Earth’s orbit, perhaps destroying the planet. More massive Miras can exceed the size of the Martian orbit. *See also:* MIRA; VARIABLE STAR.

During this activity, stars go through various stages of convective dredge-up, in which they can raise elements created in their nuclear-burning zones to the stellar surfaces. The first of these dredge-ups alters the nitrogen and carbon isotope ratios while the star is on its first ascent of the red giant branch. Above about 3 solar masses, a second dredge-up in the early AGB stage can increase both surface nitrogen and helium. In the helium-flashing state, even carbon from helium fusion can be brought upward. Moreover, a host of elements created by slow neutron capture are elevated as well, including zirconium, strontium, barium, and many others. When the carbon abundance equals that of oxygen, an S star is seen (loaded with fresh zirconium); when carbon exceeds oxygen, a genuine carbon star is seen. *See also:* CARBON STAR.

Mass loss and planetary nebulae

During the giant stages, stellar winds greatly increase. Mira pulsations cause shock waves that help drive mass from the stellar surfaces, where the cooled gas becomes ever richer in molecules, some even condensing into dust grains. High luminosity pushes the dust outward, and the dust couples with the gas, resulting in slow (10 km/s or 6 mi/s), thick winds that are tens of millions of times stronger than the solar wind (up to 10^{-5} solar mass per year). Because stars are in this state for hundreds of thousands of years, they will lose much of themselves back into space—the Sun nearly half of its mass, a 9-solar-mass star more than 80%. Advanced giants and Miras lose so much that they can visually disappear within dust clouds. Carbon star winds contain various kinds of carbon dust as well as organic molecules, while oxygen-rich stars produce silicate dust. The dust blown into interstellar space helps make new generations of stars. The elements created in the nuclear-burning shells are added to the interstellar inventory, where they too find their way into new generations of both stars and planets. A good portion of the carbon, most of the nitrogen, and significant fractions of the Galaxy's other elements come from such winds (**Fig. 5**).

So much mass is lost that an evolving star becomes stripped nearly to its fusion zone, which is protected from the outside by a low-mass hydrogen envelope. As the inner region becomes exposed, the wind diminishes in mass but increases in speed and temperature. Hammering at the surrounding dusty, molecule-filled shroud of lost mass, the high-speed wind compresses the inner edge into a thick ring. Eaten away from the top by the wind and from below by fusion, the stellar envelope shrinks, slowly exposing the hot shell-core structure beneath. When the stripped star's surface reaches 25,000 K (45,000°F), the dense ring that its high-speed wind had previously created is slowly ionized, with the degree being dependent on stellar temperature. Subsequent recapture of electrons by ions, along with collisional excitation of heavy atoms, causes the shell to glow, and a planetary nebula is born. The first of these was announced by William Herschel (who named the class on the basis of its disklike shapes) in 1785. Well over a thousand are now known (**Fig. 6**). *See also:* PLANETARY NEBULA.

As the planetary nebula, expanding at about 20 km/s (12 mi/s), grows in size, it eventually becomes so tenuous that the ionizing radiation bursts through, allowing much of the full structure to be seen. After some 50,000 years, the nebula invisibly merges with the interstellar medium. During this time, the star inside first heats at constant luminosity to over 100,000 K (180,000°F), with the luminosity and final temperature depending on the old core's mass (which ranges from around 0.5 $M_\odot$ to nearly 1.4 $M_\odot$, the Chandrasekhar limit, above which white dwarfs cannot exist). As residual nuclear fusion shuts down, the star cools and dims at constant radius to become a white dwarf. The luminosity-mass relation is now reversed, as higher mass means higher gravitational compression and smaller radius.

Made of carbon and oxygen surrounded by a thin hydrogen or helium atmosphere, the white dwarf is supported forever by degenerate electron pressure. Since the evolutionary and cooling times of white dwarfs can be calculated theoretically, the oldest of them provides an age measure for the galactic disk, and this measure accords well with that found from open clusters. *See also:* WHITE DWARF STAR.

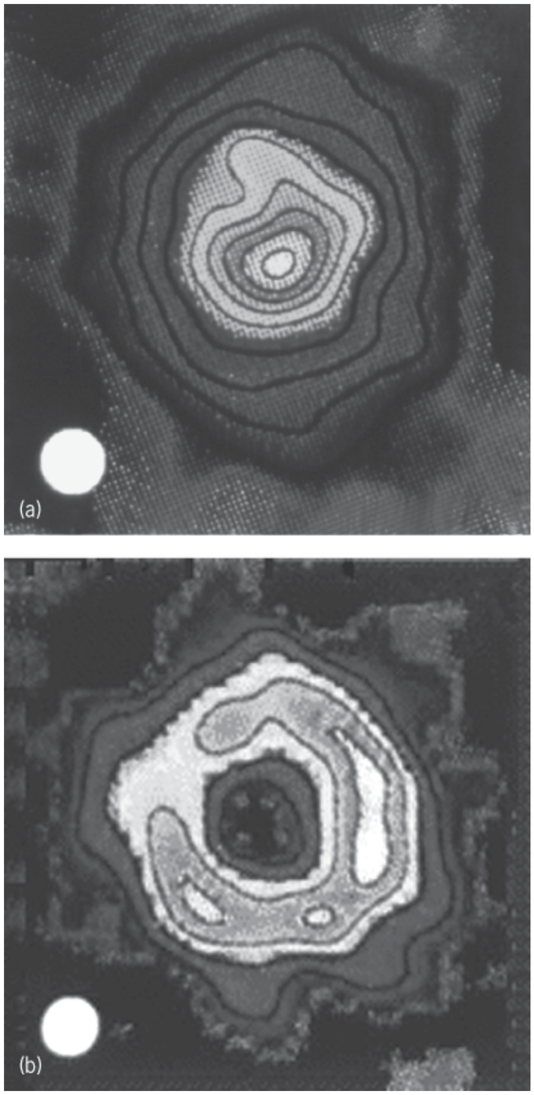

Fig. 5 **Thick molecule-filled cloud surrounding the carbon star IRC+10 216. (*a*) Image made in radiation from hydrocyanic acid (HCN). (*b*) Image in radiation from cyanoacetylene (HC_3N). Each map is 6000 astronomical units across. (*J. Bieging; Berkeley-Illinois-Maryland Association*)**

High-mass evolution

As the mass of a star increases, so does the mass of its core. The Sun will turn into a white dwarf of around 0.55 solar mass. At roughly 9 solar masses, the core reaches the Chandrasekhar limit, and the star cannot become a white dwarf. At first, the evolution of high-mass stars proceeds similarly to that of stars of lower mass. As high-mass stars use their core hydrogen, they too migrate to the right on the HR diagram, becoming not so much brighter but larger, cooling at their surfaces, and turning into supergiants. Below about 40 solar masses, they become class M red supergiants, losing huge amounts of mass through immense winds. Some (depending on mass) stabilize there by the start of helium fusion; others loop back to become blue supergiants. Above 60 solar

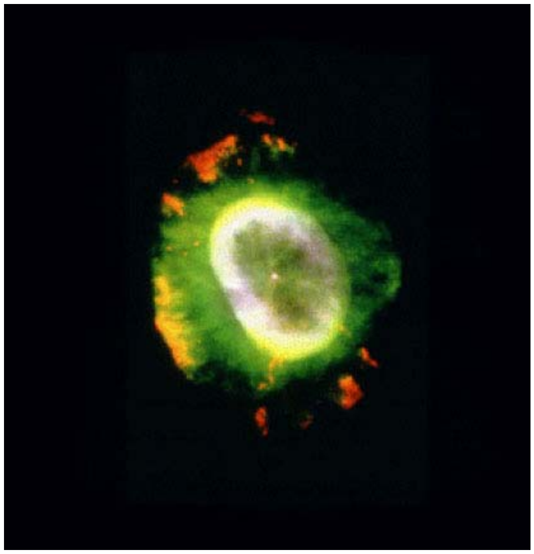

Fig. 6 *Hubble Space Telescope* image of planetary nebula NGC 7662. Planetary nebulae are formed when giant stars slough their outer envelopes, leaving a white dwarf behind. (*B. Balick et al.; Space Telescope Science Institute; NASA*)

masses, so much mass is lost through winds that the stars do not make it much past class B, stalling there as helium fusion begins (**Fig. 7**). As lower-mass supergiants—as well as bright giants—pass through the middle of the diagram, some become Cepheid variables. *See also:* CEPHEID VARIABLES; SUPERGIANT STAR.

Though almost all these supergiants vary to some extent, the most massive become unstable and undergo huge eruptions. In 1846, Eta Carinae, near 100 solar masses (and a probable double star), brightened to match Sirius and Canopus, lost more than a solar mass, and then faded to near the edge of naked-eye vision (**Fig. 8**). Such luminous blue variables (LBVs), plus similar lesser lights, are losing their hydrogen envelopes and may be turning into helium-rich Wolf-Rayet stars, highly luminous stars that have been almost completely stripped of their outer hydrogen. Though the sequence is not clear, the luminous blue variables probably first turn into the nitrogen-rich WN variety (whose nitrogen has been enriched through hydrogen fusion by the carbon cycle) and then into the carbon-rich WC species (the carbon from more advanced helium fusion).

While intermediate-star fusion stops at carbon and oxygen, supergiants continue onward. The carbon-oxygen core shrinks and heats to the point where carbon fusion can begin, and then carbon and oxygen convert to a more complex mix dominated by oxygen, neon, and magnesium. Helium fusion now continues in a surrounding shell that is nested within one that is fusing hydrogen. Once carbon burning has run its course, the unsupported oxygen-neon-magnesium core shrinks and heats, and now it is carbon burning's turn to move outward into a shell. When hot enough, the oxygen-neon-magnesium mix fires up to burn to one dominated by silicon and sulfur. Continuing the process, the developed silicon and sulfur core finally becomes hot enough to fuse in a

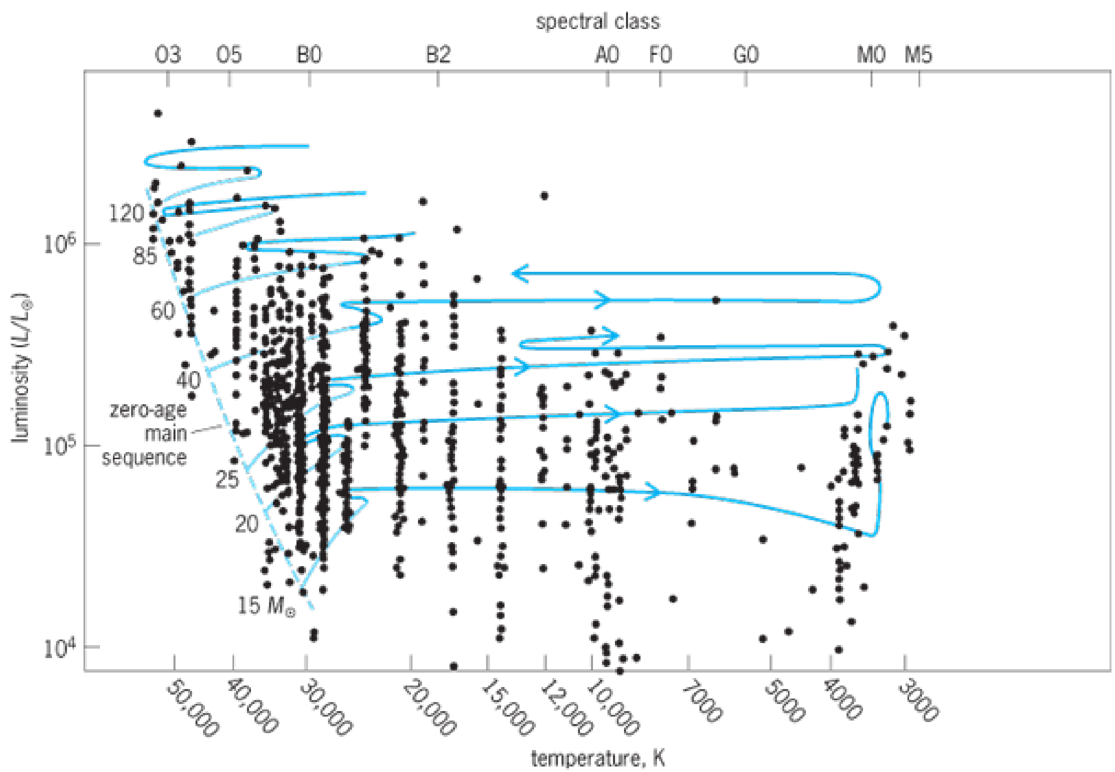

Fig. 7 Hertzsprung-Russell diagram for evolution of high-mass stars. These stars evolve to red supergiants, with some evolving back to blue supergiants. Above about 60 solar masses, evolution is stalled by extreme mass loss. (*From work of A. Maeder and G. Meynet; and R. Humphreys and K. Davidson*)

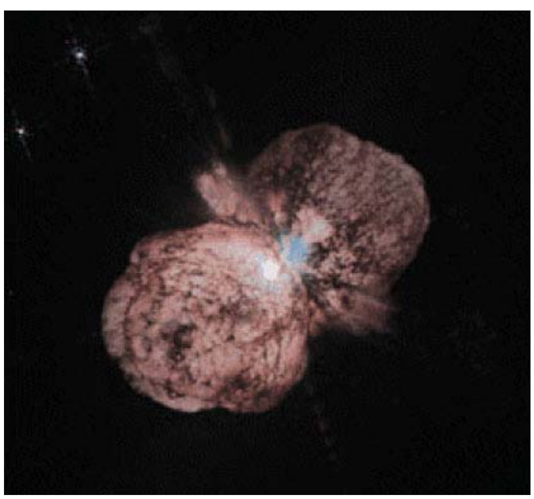

Fig. 8 ***Hubble Space Telescope*** **image of a luminous blue variable, the supergiant Eta Carinae, buried in the middle of a giant expanding cloud of its own making. (*J. Morse, University of Colorado; Space Telescope Science Institute; NASA*)**

complex way to iron, with the silicon-burning core being wrapped in oxygen-neon-magnesium-, helium-, and hydrogen-burning shells.

Supernova

Each nuclear fusion stage generates less energy, and since each takes on the role of supporting the star, each lasts a shorter period of time. While hydrogen fusion takes millions of years, the iron core is created from silicon fusion in a matter of weeks. Iron cannot fuse and produce energy. The core, about 1.5 solar masses and the size of Earth, suddenly collapses at a speed that is a good fraction of that of light. The iron atoms are broken back to neutrons and protons. Under crushing densities, free electrons merge with protons to make yet more neutrons. When the collapsing neutron core hits nuclear densities of 10^{14} g/cm^3 (10^{14} times the density of water), it bounces violently, and the rebound tears away all the outer layers.

From the outside, the observer sees the explosion as a type II supernova, which typically can reach an absolute magnitude of −18 (**Fig. 9**). Temperatures within the exploding layers are high enough that a great variety of nuclear reactions, from equilibrium fusion of one element into another to rapid neutron capture, create all the chemical elements up to and beyond uranium. The optical glow eventually comes mainly from the manufacture of a tenth or so of a solar mass of radioactive nickel, ^{56}Ni, which quickly decays to radioactive cobalt and then to stable iron, ^{56}Fe, which gets blasted into the cosmos along with everything else. *See also:* RADIOACTIVITY.

The nature of the rebound is far from understood. By itself, it does not account for the explosion of a supernova. However, the merger of core protons and electrons generates vast numbers of near-massless neutrinos. Nearly everything is transparent to them. Those that are created in the solar core by the proton-proton chain go right through the Earth. The densities around the rebounding neutron core, however, are so high that the neutrinos are trapped, and may aid in shoving the surrounding shells and envelope outward. Other ideas invoke violent convection within the neutron core to provide the energy. However it is done, the outflowing neutrinos carry away 100 times more energy than does the blast itself. For a brief moment, the power output of a single supernova equals that of the rest of the stars in the visible universe. At the highest progenitor masses, supernovae are believed to eject their energy in bipolar jets, leading to longer-duration gamma-ray bursts (GRBs). The progeny of O stars, supernovae are rare, occurring in the Milky Way Galaxy at a rate of only one or two per century, so the odds of one being close to Earth are fortunately small. *See also:* GAMMA-RAY BURSTS; NEUTRINO; SUPERNOVA.

Supernova remnants and compact remains

The debris of the explosion, the supernova remnant, highly enriched in iron and other heavy elements, expands into space for centuries. Its shock wave energizes interstellar space, heats vast bubbles of gas to hundreds of thousands of degrees, and helps compress interstellar matter and create new stars. Its heavy elements become incorporated into molecular clouds. Most of the Earth came from previous generations of supernovae, each one contributing perhaps a mountain mass. Accelerated by the shock, ambient interstellar electrons, protons, and

Fig. 9 **Field around the type II core-collapse supernova SN 1987A. (*a*) Two weeks after the supernova exploded in the Large Magellanic Cloud in 1987. The supernova far outshone its neighboring stars, and was easily visible 150,000 light-years away. (*b*) Before the explosion, it was a rather ordinary B1 blue supergiant (indicated by arrow). (*Copyright © Anglo-Australian Observatory, photograph by David Malin*)**

heavier nuclei approach the speed of light and speed through the Galaxy as cosmic rays, which in their turn also help initiate star formation (**Fig. 10**). *See also:* CRAB NEBULA; INTERSTELLAR MATTER; NEBULA; SHOCK WAVE.

Exposed by the explosion is the compact hot neutron star. Only 25 km (15 mi) across, it is stabilized by the pressure of neutron degeneracy. Conservation of angular momentum makes the little star spin dozens of times per second, its magnetic field compacted to 10^{12} or more times stronger than Earth's. Radiation beams out along a tilted, wobbling magnetic axis, and if Earth is in its path, a "pulse" of radiation is observed—the neutron star is now a "pulsar." As the neutron star radiates away its energy, it spins more slowly and finally disappears from view. The most highly magnetized neutron stars, the magnetars, can have magnetic field strengths greater than 10^{14} times that of Earth, and are related to anomalous x-ray pulsars (AXPs) and to soft gamma-ray repeaters (SGRs), the latter occasionally releasing bursts so powerful that they can affect the Earth. The Galaxy must contain more than 10^8 quiet, near-invisible neutron stars. Off-center detonation in the supernovae that created them may give them kicks that can send them off at speeds far higher than those of most of the Galaxy's stars. *See also:* NEUTRON STAR; PULSAR.

Beyond the Chandrasekhar limit of 1.4 $M_\odot$, electron degeneracy pressure cannot stabilize a white dwarf, and it must collapse. Neutron stars are close to this limit, and are themselves similarly limited to around 3 solar masses. Stars at the upper end of the main sequence are expected to create iron cores that exceed even this limiting

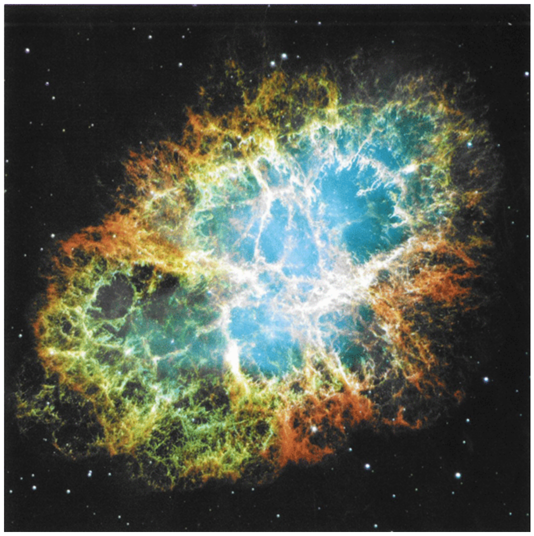

Fig. 10 **Mosaic image taken by the *Hubble Space Telescope* of the Crab Nebula, the remnant of a supernova explosion recorded by Chinese and Japanese astronomers in 1054. The image was assembled from 24 Wide Field and Planetary Camera 2 exposures in 1999 and 2000. The blue interior glow is synchrotron radiation from high-energy electrons accelerated by the Crab's central pulsar. Colors in the intricate filaments trace the light from atoms of hydrogen, oxygen, and sulfur expelled during the explosion. (*NASA; ESA; J. Hester and A. Loll, Arizona State University*)**

mass. The dense remains cannot stabilize, and therefore they too must collapse. When such a collapsing star passes a critical radius at which the escape velocity is about that of light, it become invisible, and a black hole is born. About a dozen black hole candidates are recognized in binary systems in which the black hole affects the companion. *See also:* BLACK HOLE.

Double-star evolution

Double (binary) stars are a common fact of stellar life. Within wide margins, more than half the galaxy's stars are at least double. If the components of a binary are well separated (by tens or hundreds of astronomical units), the stars evolve separately as if each were single. If the stars are close enough together, however (the critical limits being dependent on mass), they can profoundly affect each other and their courses of evolution.

A binary is first made of a pair of dwarf stars. The more massive evolves first into a giant or even a supergiant. If the two are close enough to start with, the growing giant can be affected by the smaller star. As it swells, it approaches a teardrop-shaped tidal surface in which the gravitational pulls from the two stars (including the forces resulting from orbital motion) are effectively equal. If the giant or supergiant actually reaches the zero-gravity surface, mass can flow through the point of the teardrop toward the smaller star. If the two still have sufficient separation, the incoming matter will first flow into a disk around the dwarf, from which the dwarf will accrete mass. If the two are close enough, matter will impact the dwarf directly without forming a disk. In either

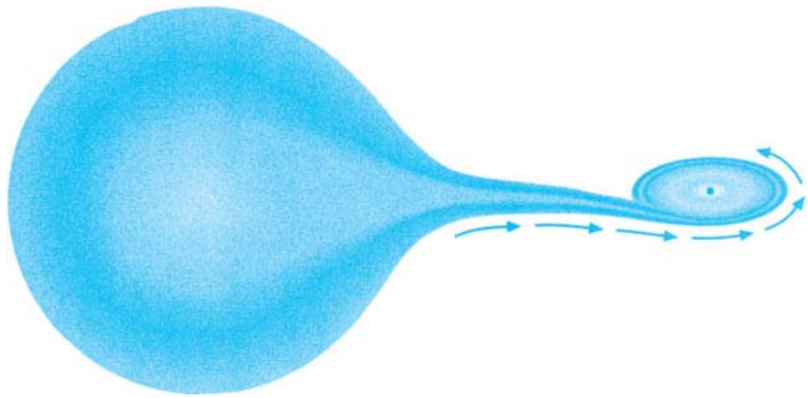

Fig. 11 A star fills its tidal surface and passes mass on to a white dwarf in preparation for a nova or even a type Ia supernova. (*From J. B. Kaler, The Little Book of Stars, Copernicus Books, New York, 2000*)

case, the result is that mass will be transferred, resulting both in interesting spectral activity and in the more massive star eventually becoming the less massive. Among the most dramatic examples of this kind of behavior is the eclipsing binary Algol, in which a class B dwarf accretes mass from a K giant. Mass loss can also wrap the pair in a common envelope. That and angular momentum losses resulting from the close interaction as well as from interacting magnetic fields can draw the two closer together and perhaps even make them merge.

The giant eventually produces a planetary nebula and then becomes a white dwarf. Mass loss has left the white dwarf with almost no hydrogen, perhaps only a thin skin on its surface. If the two stars have been drawn close enough together, the white dwarf can tidally stretch the remaining dwarf (usually a G, K, or M star) to the zero-gravity surface, which can then transfer mass, mostly hydrogen, back to the white dwarf (**Fig. 11**). Instabilities in the accretion disk, as well as ionization and illumination of the flowing stream by a hot spot created by interacting gases, make the pair a flickering cataclysmic variable (CV). When the fresh hydrogen layer is thick, compressed, and hot enough, it burns explosively via the carbon cycle, with the thermonuclear runaway creating a nova that brightens to absolute visual magnitude M_V = - 10 or so. Several are seen each year, with one of first magnitude every few decades. Since a nova is only a surface phenomenon and does not much affect the stars of the binary, the system settles back into its prior CV behavior, and after 10^5 years may produce a nova explosion again. *See also:* CATACLYSMIC VARIABLE; NOVA.

In wider dwarf–white dwarf combinations, the ordinary dwarf will eventually begin its own evolution and become a giant. If it received mass from its companion when it was a dwarf (perhaps through a wind), the giant may have been contaminated with by-products of nuclear fusion and appear as a barium star, anomalously rich in barium and other elements. As the giant grows, it passes its mass to the white dwarf through its vigorous wind or via an accretion disk. The hot white dwarf, or a hot boundary layer between an accretion disk and the white dwarf's surface, now gives the binary dual characteristics, those of both a hot and a cool star at the same time.

These symbiotic stars can vary dramatically, and the transferred hydrogen can erupt into long-term fusion reactions. *See also:* SYMBIOTIC STAR.

White dwarf supernovae

There are two quite different kinds of supernovae. Type II supernovae have hydrogen in their spectra. They occur in galactic disks, where young high-mass stars reside, and are produced by iron-core collapse. Type I events, however, do not exhibit spectral hydrogen. They are divided into three categories: Type Ia supernovae display an absorption line of ionized silicon, whereas those of type Ib exhibit helium instead of silicon, and those of type Ic have neither (or weak helium). While Ib and Ic supernovae are also confined to the disks of host galaxies, Ia supernovae occur in both disks and galaxy haloes, where there are no high-mass stars. Tycho's Star of 1572 and possibly Kepler's Star of 1604 were type Ia (although some argue that the latter was type II).

The Ib variety (and some of the Ic) is probably produced by core collapse in massive hydrogen-poor Wolf-Rayet stars. White dwarfs in double systems are obvious candidates for type Ia. The more massive the receiving white dwarf, the more quickly the infalling fresh hydrogen reaches the nova flash point. If the white dwarf is massive enough, the interval between successive novae becomes less than the time over which the novae have been observed, and the novae become recurrent. For example, RS Ophiuchi and its cohort produce a nova every 20 years or so. Each nova leaves a little residual matter, so the white dwarf increases in mass. If it is pushed over the Chandrasekhar limit, the star must catastrophically collapse and burn, producing a type Ia supernova (although it is contended that recurrent novae and Ia supernovae are actually related). A second scenario that might produce type Ia supernovae is the merger of the stars in a double white dwarf system in which the sum of the masses exceeds the Chandrasekhar limit. Type Ia supernovae are even brighter than core-collapse type II events, and can reach $M_V = -19$. They are exceeded only by rare core-collapse events that are probably related to GRBs. They also deposit more iron into the cosmos than do the type II, typically three-tenths of a solar mass. All the iron in the universe is made by supernovae. *See also:* WOLF-RAYET STAR.

Though the origins of type Ia explosions are not very well understood, the supernovae have such predictable absolute magnitudes that they can be used to measure distances to distant galaxies and determine not just the Hubble constant but also more subtle expansion characteristics of the universe.

Heavy-element enrichment

Many of the preceding scenarios are still shrouded in mystery. Not all the doubles have all the behavior patterns described, and there are great numbers of categories of each kind of phenomenon. The overall result of stellar evolution is clear, however. As stars become giants that turn into white dwarfs, or as they become supergiants that create neutron stars or black holes, they feed huge quantities of enriched matter back into the star-generating clouds of interstellar space. Later generations of stars therefore have more heavy elements than do earlier generations. Computer modeling of the chemical composition of the Galaxy, starting with the hydrogen and helium of the big bang, can closely replicate the chemical composition of the Sun, providing powerful evidence that the theories are correct. The Earth, made almost entirely of heavy elements, is a distillate of solar gases, and exists only as a result of the combined action of the stars.

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Keywords

stellar model

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Stellar Evolution

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Virtual Trips to Black Holes and Neutron Stars