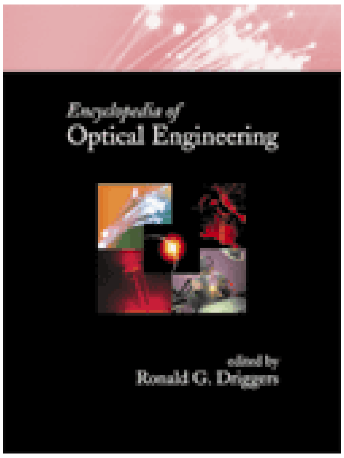

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Stellar Evolution

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Stellar Evolution

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INTRODUCTION

Stars have a birth, life, and death. They are created deep within gaseous nebulae—immense clouds of gas and dust. Shortly thereafter, the stars emerge from these cocoons, and for most of their lives, exist quietly and stably. Near the end of their lives, though, as their nuclear fuel becomes depleted, the stars die and return a portion of their outer layers back to the interstellar medium (ISM). Eventually another gaseous nebula forms from this enriched material, and a new generation of stars is created.

The key quantity that dictates the evolution of a single star is its mass. The ‘‘weight’’ of a star must be balanced by internal pressure from rapidly moving particles and energetic photons. Under these extreme conditions, nuclear reactions occur. For higher-mass stars, greater pressures and temperatures are required to balance the gravity. These stars have more mass (fuel) than do low-mass stars, but the corresponding ‘‘fire’’ in their interiors is much greater, so the nuclear reactions occur at a quicker rate. Massive stars literally ‘‘eat themselves up’’ at an enormous speed. A star 20 times the mass of the Sun (i.e., 20 $\mathcal{M}_\odot$) may live for only a few tens of millions of years. The Sun (1.0 $\mathcal{M}_\odot$) will live for 10 billion years, and a low-mass star of 0.2 $\mathcal{M}_\odot$ will survive for more than 100 billion years.

BIRTH

Nebulae

The region between stars is known as the interstellar medium. Although the average density is only about 1 hydrogen atom/cm^3, the ISM is not empty. Within the ISM are giant clouds, known as nebulae, of which there are a variety of types. A gaseous nebula has a density of about 1000 hydrogen atoms/cm^3, but because the volume encompasses tens of cubic parsecs, the mass may be as much as 10,000 $\mathcal{M}_\odot$. Hundreds or thousands of stars will be created in one of these ‘‘stellar nurseries.’’ Single, isolated stars are never formed.

In order for stars to develop, there must be regions in the nebula where the density is high and the temperature is low. These conditions make for a strong gravitational attraction and a weak internal pressure. Such regions appear dark because of the high opacity and the presence of dust grains, which obscure background light. These nebulae have densities reaching 10,000 particles/cm^3 yet maintain 10 K temperatures, unlike the hot gaseous nebulae that have temperatures of 10,000 K.

Protostars

The first phase of stellar birth is the gravitational collapse of small mass concentrations in a nebula. The process is quite rapid, taking only a few thousand years to form a protostar cloud, which is about the size of the solar system. At this point, the increase in temperature, pressure, and density significantly slow the shrinkage of the protostar cloud. Depending upon the amount of mass in the protostar, the slower, gravitational contraction phase lasts from only a few thousand years for the very massive stars to 100,000 years for stars like the Sun to tens of millions of years for the lowest mass stars. These are relatively short processes, though, compared to the star's full lifetime, typically measured in billions of years. Fig. 1 and Table 1 show the evolutionary tracks and time intervals for several solar mass values.

As the protostar continues its slow contraction, the inner regions become quite hot (2000–3000 K) from the conversion of gravitational energy to thermal energy. Convective currents develop to transport the heat from the core to the cooler outer regions. The protostar becomes hotter and smaller. For the lower-mass protostars the luminosity increases, whereas it remains constant for the high-mass protostars. The brightness is not because of thermonuclear reactions but rather to the conversion of potential energy to kinetic energy. Observers do not ‘‘see’’ such protostars, though, for they are shrouded deep within the dusty and opaque cloud. (Infrared and radio wavelength observations can penetrate the cloud and detect these objects, though.)

As the protostar continues to contract, a point is reached where the temperatures and pressures are sufficiently high that thermonuclear burning begins (i.e., the fusion of hydrogen to helium). Relating the life of a star to that of a human, stellar ‘‘birth’’ occurs when the hydrogen

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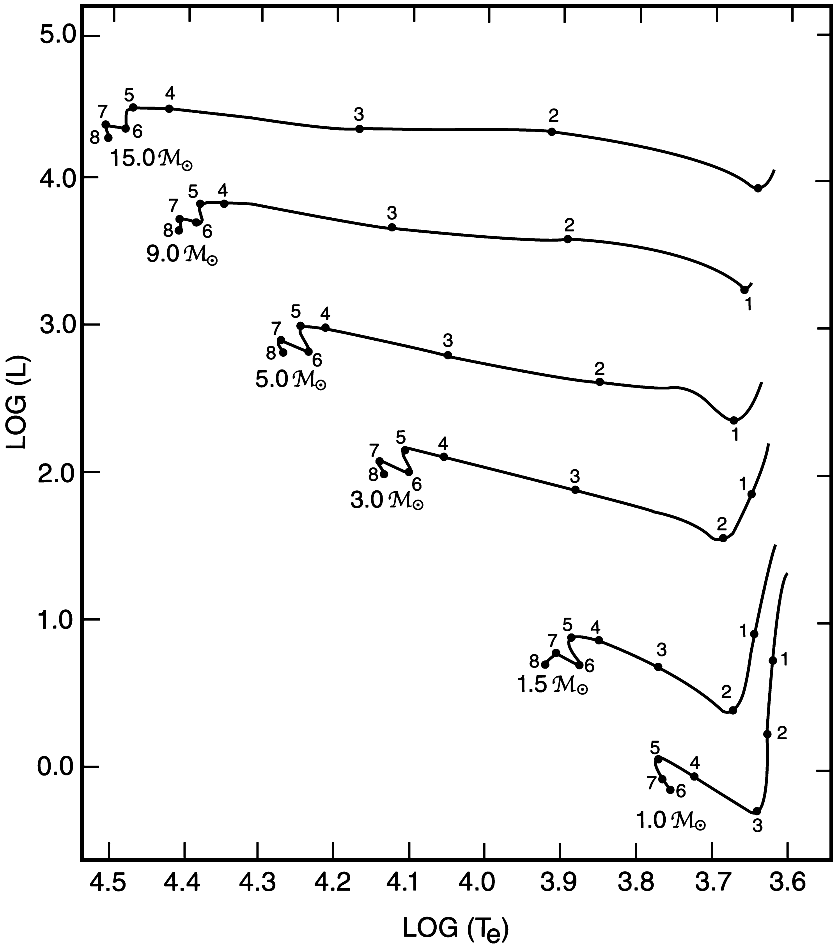

Fig. 1 An HR diagram showing pre-main-sequence evolutionary tracks for a variety of stellar masses. Times corresponding to the indicated points are listed in Table 1. (From Iben, I., *Astrophys. J.*, 141, 1010, 1965.)

thermonuclear reactions begin in the core. By definition, the object is now a star, and its location on the HR diagram is the main sequence.

The star goes through a relatively brief—and still unexplained—period known as the T Tauri phase (named after the prototypical star) having a strong stellar wind that blows away the remaining shroud of gas and dust, which may be as much as 75% of the original protostar cloud. The star becomes visible and settles into a long period of stability and constant luminosity.

Table 1 Lifetimes for pre-main-sequence stars

Point	15.0 $\mathcal{M}_\odot$	9.0 $\mathcal{M}_\odot$	5.0 $\mathcal{M}_\odot$	3.0 $\mathcal{M}_\odot$	1.5 $\mathcal{M}_\odot$	1.0 $\mathcal{M}_\odot$
1	6.740×10^2	1.443×10^3	2.936×10^4	3.420×10^4	2.347×10^5	1.189×10^5
2	3.766×10^3	1.473×10^4	1.069×10^5	2.078×10^5	2.363×10^6	1.058×10^6
3	9.350×10^3	3.645×10^4	2.001×10^5	7.633×10^5	5.801×10^6	8.910×10^6
4	2.203×10^4	6.987×10^4	2.860×10^5	1.135×10^6	7.584×10^6	1.821×10^7
5	2.657×10^4	7.922×10^4	3.137×10^5	1.250×10^6	8.620×10^6	2.529×10^7
6	3.984×10^4	1.019×10^5	3.880×10^5	1.465×10^6	1.043×10^7	3.418×10^7
7	4.585×10^4	1.195×10^5	4.559×10^5	1.741×10^6	1.339×10^7	5.016×10^7
8	6.170×10^4	1.505×10^5	5.759×10^5	2.514×10^6	1.821×10^7	

The times are in years, and the points are indicated on the HR diagram in Fig.1. From Iben, I., Astrophys. J., 141, 1010, 1965.

There are several unexplained aspects of protostar development.

1. Lower mass limit—Objects under 0.08 $\mathcal{M}_\odot$ are not able to generate thermonuclear reactions. These ''brown dwarfs'' are technically not stars nor are they planets, for Jupiter's mass is only 0.001 $\mathcal{M}_\odot$. Many brown dwarfs should exist, but only a few candidates have been identified.
2. Upper mass limit—The upper mass limit is harder to calculate, but it is somewhere from 50 to 100 $\mathcal{M}_\odot$. (Stars above 30 $\mathcal{M}_\odot$ are extremely rare.) The internal pressures are so much greater than the self-gravities that these stars are blown apart from within.
3. Mass distribution—The cluster of stars that is formed contains many more low-mass stars than intermediate mass ones. Likewise, there are more intermediate mass objects than high-mass stars. As stellar mass increases, the number of stars per that mass decreases.
4. Multiple stars—About half of the protostars form gravitationally-bound binary star systems. It is believed that single stars are the only ones that can be encircled with planets.

LIFE

Main Sequence

The time that a star spends fusing hydrogen in the core is its main sequence lifetime. This is by far the longest phase of a star's evolution. The actual time is correlated with the total mass: $\tau \propto \mathcal{M}^{-2.5}$—the higher the mass, the shorter the main sequence lifetime. The luminosity of a main sequence star is also directly correlated with its mass: $L \propto \mathcal{M}^{3.5 \text{ to } 4.0}$—the higher the mass the significantly brighter the star.

There are only two or three distinct layers inside a star. The core is the innermost region, and this is where the nuclear reactions occur. The rest of the interior transports the light and heat from the core. Stars more massive than ~ 4 $\mathcal{M}_\odot$ accomplish the transport first by an inner convective zone and then by an outer radiative region, where the opacity is low. The positions of these zones are reversed in the low-mass stars because the opacity near the surface is quite high, preventing radiative flow. The convective zone stretches from the core to the surface in stars under 0.8 $\mathcal{M}_\odot$.

It is within the core that almost all of the light is generated, though the photons do not travel far. The majority of photons generated are in the X-ray region. These photons travel only a millimeter before interacting with matter. Through subsequent reemission and random walks, these photons work their way out, but it takes about a million years for such a photon to reach the star's surface and escape. During its journey, the photon loses energy and emerges in the ultraviolet/optical/infrared wavelength region.

The luminosity of a star is produced by the conversion of matter to energy via Einstein's equation, $E = mc^2$ (energy is equal to mass times the speed of light squared). The set of nuclear reactions that convert four hydrogen nuclei into one helium particle is known as the proton–proton chain reaction:

$$^1\mathrm{H} + {}^1\mathrm{H} \rightarrow {}^2\mathrm{H} + \mathrm{e}^+ + \nu$$

$$^1\mathrm{H} + {}^2\mathrm{H} \rightarrow {}^3\mathrm{He} + \gamma$$

$$^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + {}^1\mathrm{H} + {}^1\mathrm{H}$$

where ^{1}H is one proton, ^{2}H is deuterium (one proton and one neutron), ^{3}He is a helium nucleus consisting of two protons and one neutron, ^{4}He is a helium nucleus with two protons and two neutrons, e^+ is a positron, ν is a neutrino, and γ is a photon. The mass of four individual hydrogen nuclei (protons) is greater than the total mass of two protons and two neutrons in a helium nucleus. It is the difference in these masses that is converted into energy.

High-mass stars can also fuse four hydrogen nuclei into one helium nucleus by a series of nuclear reactions that use carbon, nitrogen, and oxygen as catalysts. This series is known as the CNO cycle. It requires higher temperatures and a large abundance of the catalysts. The sequence of reactions is:

$$^{12}\mathrm{C} + {}^1\mathrm{H} \rightarrow {}^{13}\mathrm{N} + \gamma$$

$$^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + \mathrm{e}^+ + \nu$$

$$^{13}\mathrm{C} + {}^1\mathrm{H} \rightarrow {}^{14}\mathrm{N} + \gamma$$

$$^{14}\mathrm{N} + {}^1\mathrm{H} \rightarrow {}^{15}\mathrm{O} + \gamma$$

$$^{15}\mathrm{O} \rightarrow {}^{15}\mathrm{N} + \mathrm{e}^+ + \nu$$

$$^{15}\mathrm{N} + {}^1\mathrm{H} \rightarrow {}^{12}\mathrm{C} + {}^4\mathrm{He}$$

The end result is the same as in the proton–proton cycle: Four hydrogen nuclei have formed one helium nuclei and the fusion process has generated energy.

As a star sits quietly on the main sequence fusing hydrogen into helium, small structural changes occur. The core was initially composed (by weight) of about 74% hydrogen, 25% helium, and 1% everything else. With time, though, additional helium nuclei are produced and hydrogen is depleted. As the amount of helium increases, it gathers in the central core. The temperature and pressure in the core are not yet sufficiently high to fuse helium into heavier elements. Now the internal structure of the star has changed—there is a small, nonburning helium core surrounded by a hydrogen-burning shell. The helium core does not contribute to the energy production; in fact, it robs energy as the hydrogen-burning shell ‘‘pushes’’ on the core, making it extremely compact.

A star is a self-contained physics experiment, and all of the conservation laws apply. When a change of temperature, pressure, or density occurs in the core, the rest of the star has to adjust in order to maintain equilibrium. A good example of this interplay is the relationship between a star’s luminosity, radius, and surface temperature:

$$L = 4\pi R^2 \sigma T^4$$

where σ is the Stefan–Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}). Two internal changes have been occurring. First, the density profile has increased radically as the helium core has been created and highly compressed. Second, the hydrogen shell has been producing additional luminosity to balance the self-gravity. In response, the outer layers initially expanded to increase the potential energy, and later they continued to expand due to the increase in energy generation by the hydrogen-burning shell.

As the outer layers expand to 10–20 $\mathcal{R}_\odot$, convective currents increase in the outer layers and the surface temperature decreases to about 3500 K. The total luminosity increases, though, and the star moves away from the main sequence toward the red giant region. Evolutionary tracks off the main sequence are indicated for various solar masses in Fig. 2 and Table 2.

Low-Mass Stars

At this point, the total mass of a star dictates one of two very different evolutionary paths. For the low-mass stars

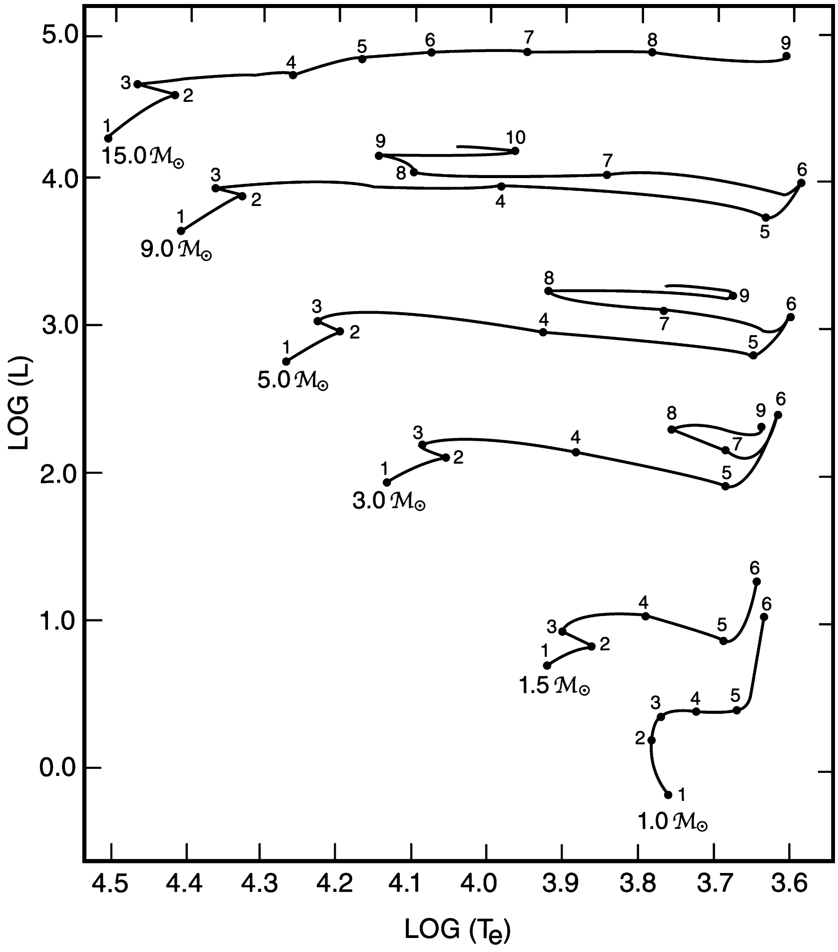

Fig. 2 An HR diagram showing main-sequence and post-main-sequence evolutionary tracks for a variety of stellar masses. Times corresponding to the indicated points are listed in Table 2. (From Iben, I., *Astrophys. J. (Lett.)*, 140, 1632, 1964.)

Table 2 Lifetimes for main-sequence and post-main-sequence stars

Point	**15.0 $\mathcal{M}_\odot$**	**9.0 $\mathcal{M}_\odot$**	**5.0 $\mathcal{M}_\odot$**	**3.0 $\mathcal{M}_\odot$**	**1.5 $\mathcal{M}_\odot$**	**1.0 $\mathcal{M}_\odot$**
1	6.160×10^4	1.511×10^5	5.760×10^5	2.510×10^6	1.821×10^7	5.016×10^7
2	1.023×10^7	2.129×10^7	6.549×10^7	2.273×10^8	1.567×10^9	8.060×10^9
3	1.048×10^7	2.190×10^7	6.823×10^7	2.394×10^8	1.652×10^9	9.705×10^9
4	1.050×10^7	2.208×10^7	7.019×10^7	2.478×10^8	2.036×10^9	1.024×10^{10}
5	1.149×10^7	2.213×10^7	7.035×10^7	2.488×10^8	2.105×10^9	1.045×10^{10}
6	1.960×10^7	2.214×10^7	7.084×10^7	2.531×10^8	2.263×10^9	1.088×10^{10}
7	1.210×10^7	2.273×10^7	7.844×10^7	2.887×10^8		
8	1.213×10^7	2.315×10^7	8.524×10^7	3.095×10^8		
9	1.214×10^7	2.574×10^7	8.782×10^7	3.262×10^8		
10		2.623×10^7				

The times are in years, and the points are indicated on the HR diagram in Fig. 2. From Iben, I., Astrophys. J. (Lett.), 140, 1632, 1964.

$(<4\ \mathcal{M}_\odot)$, the pressure of the hydrogen-burning shell on the helium core compresses the electrons into the quantum mechanical state known as electron degeneracy. In this configuration, the electrons become closely ''stacked'' in space, separated by the Pauli exclusion principle: No two electrons can have the same four quantum numbers relating to energy and motion in a very tiny volume. Basically, the electrons can only be pushed so close together. The electrons no longer behave as an ideal gas—the temperature (speed) of the electrons increases but the electron pressure does not change. However, the helium nuclei still behave as an ideal gas.

For stars under 0.5 $\mathcal{M}_\odot$, the temperature and pressure inside the degenerate electron core will never be great enough to begin the fusion of helium, and these stars will live for hundreds of billions of years as their hydrogen is slowly consumed.

For stars in the 0.5 to 4 $\mathcal{M}_\odot$ range, a different future awaits them. The helium core continues to grow in mass until it can no longer support itself. Now the temperature is so high (100 million degrees) that helium fusion begins, which releases much more energy. But the high pressure does not instantly decrease as it would in an ideal gas because the compact core is still in the electron degenerate state. Consequently, the newly ignited, helium-burning reactions race through the entire core—which is about the size of the Earth—in under a second. There is an incredible release of energy, known as the helium flash, which not only removes the electron degeneracy, but also adds such additional pressure to the surrounding hydrogen-burning shell that its density decreases and ceases to burn. The outer layers of the star, feeling less support, respond by contracting. Even though the core's helium flash is as bright as $10^{11}\ \mathcal{L}_\odot$, the luminosity at the surface decreases. After a short while, the star resettles into a stable configuration of a helium-burning core surrounded by a hydrogen-burning shell. This star is a red giant, and it maintains this scenario for approximately one-tenth that of its main sequence lifetime, until it begins to die.

High-Mass Stars

The evolution of O and B stars is different from that of the low-mass ones. The first major deviation occurs while the nonburning helium core is developing. Because the internal temperatures and pressures are so intense, helium nuclei begin to fuse before the core becomes electron degenerate. There is no violent helium flash to disrupt the energy production. The burning of helium primarily produces carbon and some oxygen, by the reactions:

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

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

$$^{12}\mathrm{C} + {}^{4}\mathrm{He} \rightarrow {}^{16}\mathrm{O} + \gamma$$

where $^{4}\mathrm{He}$ is helium, $^{8}\mathrm{Be}$ is beryllium, $^{12}\mathrm{C}$ is carbon, $^{16}\mathrm{O}$ is oxygen, and γ is a photon. Again, the sum of the masses of the initial nuclei is greater than the mass of the final product. This scenario continues for several sets of reactions. Carbon burning produces more oxygen, and the fusion of oxygen makes silicon.

$$^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{16}\mathrm{O} + {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$$

$$^{16}\mathrm{O} + {}^{16}\mathrm{O} \rightarrow {}^{28}\mathrm{Si} + {}^{4}\mathrm{He}$$

The last element created in the core is iron (Fe) by the burning of silicon (Si).

The paths on the HR diagram are different, too (see Fig. 2). Once these stars leave the main sequence, they quickly grow in size to the supergiant regime ($\sim$100 $\mathcal{R}_\odot$). These extended stars, already extremely luminous, do not increase their intrinsic brightness. The surface temperature decreases, and the stars quickly become red supergiants. These supergiants move to the right (redward) while the inner core is not burning, and then move quickly back across the HR diagram to the blue supergiant region when the core material ignites. The interior structure will ultimately have many shells of various nuclear reactions.

Variable Stars

All stars experience one or more phases of brightness variability during their lifetimes. The variability is not due to a change in the energy output by the core, but in the ability of the outer atmospheric layers to transport the energy to the surface. Much of the variability is due to a layer of opaqueness that ''bottles'' up some of the energy for a short while. The star cannot contain the bottled energy for long, and soon it adds an additional outward push on the higher layers. As these layers expand, the opaqueness decreases and the stored energy escapes. However, these layers do not have enough pressure support to remain extended, so they contract. As the diameter decreases and the density grows, the opaqueness begins again to increase, and the pulsation cycle repeats itself.

On the HR diagram there are several locations where variability occurs (see Fig. 3). These regions are known as instability strips. A star's evolutionary track may take it through one or more of these regions. Variable stars are usually named after a prototype in a given instability strip. Variable star designations are a running discovery sequence code (using letters or numbers) and the constellation name. Table 3 lists several types of intrinsic variables and their characteristics.

One of the first variable stars discovered was δ Cephei by John Goodricke in 1784. The ''Cepheids'' are pulsating yellow supergiants, with periods ranging from a few days to many hundreds of days. The pulsation mechanism is an opacity change as a helium layer fluctuates between being neutral or singly ionized as the star varies its size. In 1912, Henrietta Leavitt, studying Cepheids in the Small Magellanic Cloud (a nearby galaxy), determined a relationship between the pulsation period and

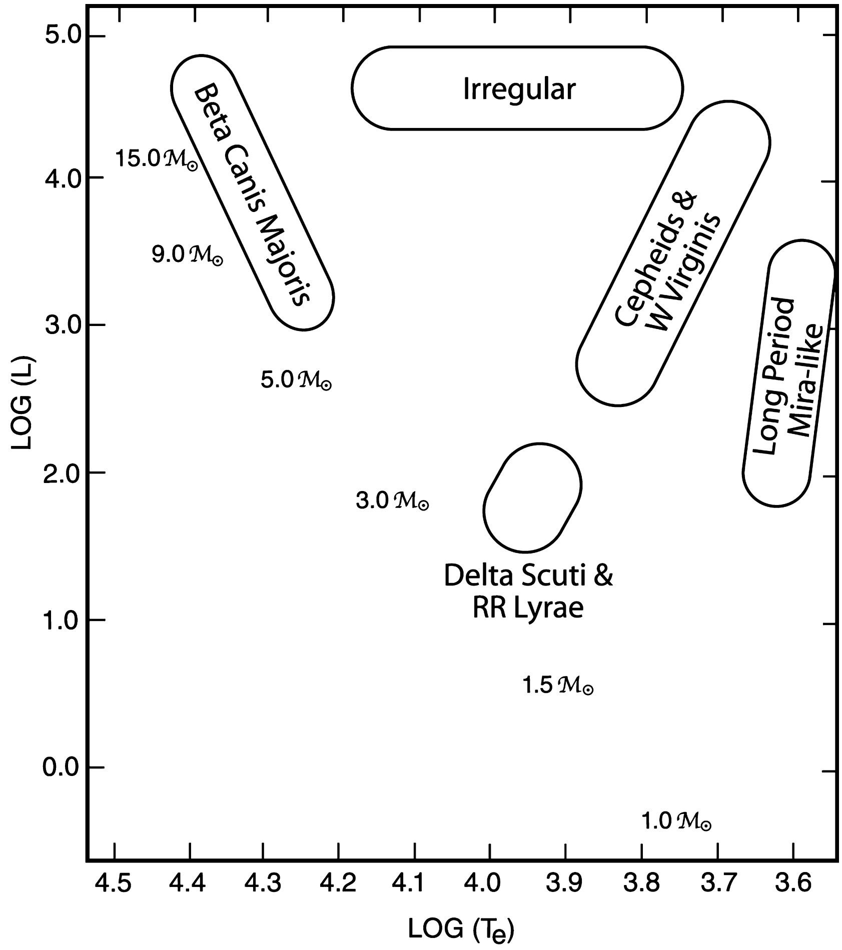

Fig. 3 An HR diagram indicating various pulsation instability strips.

Table 3 Types of variable stars

Name of variable	Type of star	Amplitude (mag)	Period (days)	Description
Cepheids	F and G supergiants	0.1 to 2	3 to 50	Regular pulsation. Period–luminosity relation exists.
W Virginis	F and G supergiants	0.1 to 2	5 to 30	Regular pulsation. Period–luminosity relation exists.
δ Scuti	F subgiants	< 0.25	0.5 to 1	Very regular, small-amplitude pulsations.
RR Lyrae	A and F giants	< 1 to 2	0.5 to 1	Very regular, small-amplitude pulsations.
RV Tauri	G and K bright giants	Up to 3	30 to 150	Alternate large and small maxima.
Long Period (Mira-type)	M red giants	> 2.5	80 to 600	Large-amplitude, semiperiodic variations.
Semiregular	M giants and supergiants	1 to 2	30 to 2000	Periodicity not dependable; often interrupted.
β Cephei	B giants	0.1	0.1 to 0.3	Maximum light occurs at time of highest compression.
T Tauri	Young G to M stars	< 3	Irregular	Rapid and irregular variations.
R Coronae Borealis	F to K supergiants	1 to 9	10 to 300	Sudden and irregular drops in brightness.
Novae	O to A binary systems	7 to 16	—	Eruptive event with the ejection of a shell.
Supernovae (Type I)	White dwarfs in binary systems	15 or more	—	Catastrophic collapse of a white dwarf.
Supernovae (Type II)	Massive supergiants	15 or more	—	Catastrophic explosion of a massive, evolved star.

the average, intrinsic luminosity. Being extremely bright, Cepheids are used to determine distances to nearby galaxies, once their pulsation periods and apparent brightness are ascertained. W Virginis stars are the Population II equivalent of Cepheids. The major difference is that the Cepheids are about twice as bright.

Another common class of variables are the RR Lyrae stars. These objects have extremely regular but very short periods (under 1 day) and have the same average intrinsic luminosity. These variables are not as bright or as large as the Cepheids, but being Population II stars, they are useful for distance determinations to globular clusters and nearby elliptical galaxies, where they are more common. Delta Scuti stars are Population I equivalents of the RR Lyrae stars.

DEATH

Planetary Nebulae

The defining role that mass plays is no more evident than in the evolutionary tracks for dying stars. Those under ~4 $\mathcal{M}_\odot$ die nonviolently via the ejection of a planetary nebula. Planetary nebulae are not related to planets—they obtained this name when astronomers first viewed them through telescopes, for they had a disklike appearance and therefore looked like small planets. Fig. 4 is an image of the Ring Nebula.

All stars under 4 $\mathcal{M}_\odot$ have some type of electron degenerate core. Stars under ~0.5 $\mathcal{M}_\odot$ have an electron degenerate helium core surrounded by a hydrogen-burning shell. Stars from 0.5 to 4 $\mathcal{M}_\odot$ have a carbon–oxygen degenerate core surrounded by an inner helium-burning shell and an outer hydrogen-burning shell. For all of these stars, there comes a time in their evolution when they need to begin thermonuclear reactions in the degenerate core. The outer layers have swollen to an enormous size (as great as 100 $\mathcal{R}_\odot$), but the temperatures and pressures in the core cannot lift the electron degeneracy or begin nuclear reactions. The evolutionary path on the HR diagram is rather similar to that of the red giants, except these stars are larger and brighter; they are called asymptotic giant branch (AGB) stars.

The ejection mechanism of their outer layers is not well understood. AGB stars are cool (~3000 K), so carbon molecules are able to form in the atmosphere. Also, AGB stars have strong stellar winds and experience sudden bursts in luminosity. All of these phenomena probably contribute to the ejection mechanism. Somehow—over the course of hundreds of thousands of years—the outer layers are gently pushed away at a speed around 30 km/s. The extremely hot core (100,000 K) is exposed, and it excites the ejected matter with ultraviolet radiation, causing the nebula to glow by fluorescence.

A typical planetary nebula has a diameter of about 1 light-year (0.3 pc) and a mass of ~0.2 $\mathcal{M}_\odot$. Planetary nebulae survive for only a few tens of thousands of years

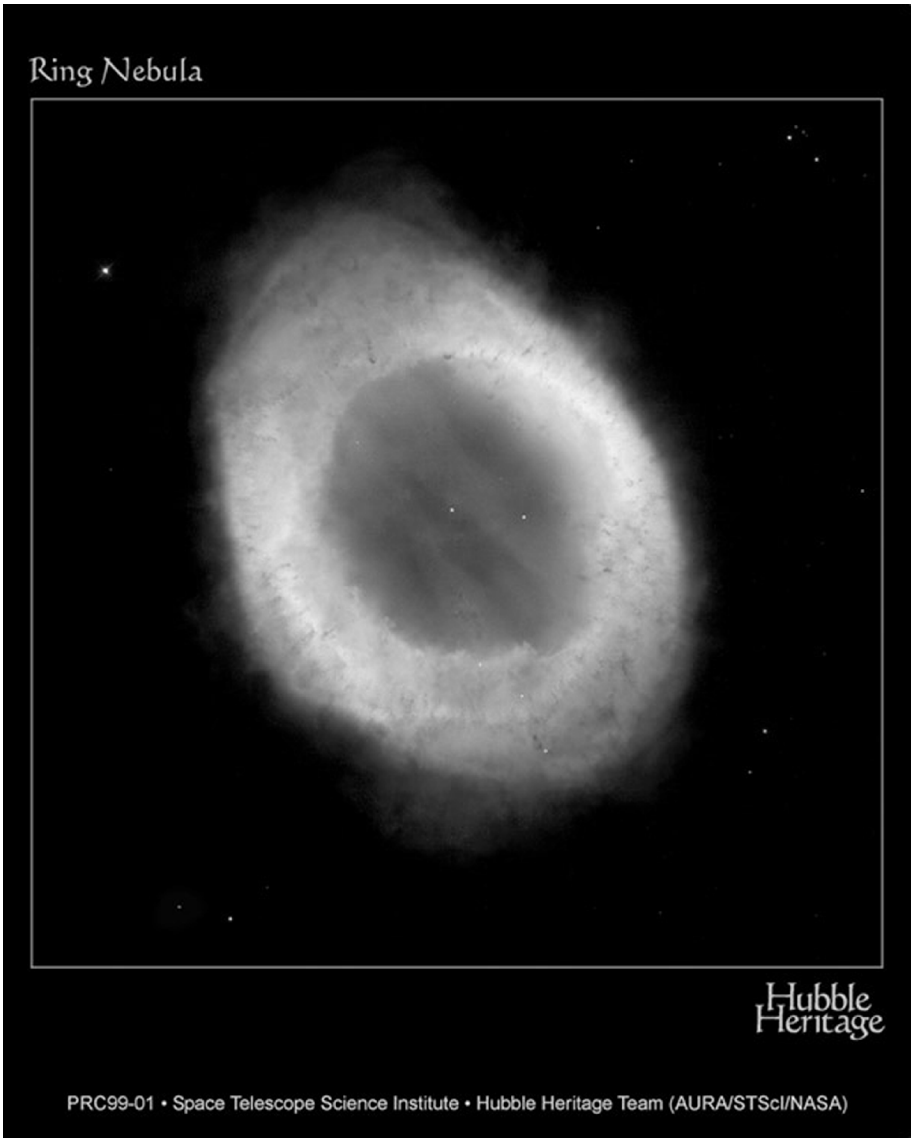

Fig. 4 The Ring Nebula is a planetary nebula, formed by the gentle expansion of the outer atmosphere of a low-mass, dying star. The white dwarf remnant can be seen in the middle of the ring. (This image was obtained with the Hubble Space Telescope.)

before they dissipate into the interstellar medium. Although this is a very rapid event on astronomical timescales, approximately 50,000 planetary nebulae are believed to currently exist.

White Dwarfs

White dwarfs are the final end product for the low-mass stars ($< 4\ \mathcal{M}_\odot$). These objects are the size of the Earth, yet have the mass of the Sun. Because the Earth is about one one-hundredth the diameter of the Sun, the average density of a white dwarf is 100^3 times greater than the Sun's density, which would be about 10^6 g/cm^3. One cubic centimeter of white dwarf material has a mass of 1000 kg (2000 lb). This result is not too surprising, for white dwarfs are the electron degenerate cores of low-mass stars.

Because white dwarfs are supported by electron degeneracy, an unusual relationship exists. When comparing two white dwarfs of different masses, the more massive star is smaller in diameter. Calculations show that the maximum possible mass is 1.4 $\mathcal{M}_\odot$, because higher masses cannot be supported by the electron degeneracy. Subrahmanyan Chandrasekhar calculated the 1.4 $\mathcal{M}_\odot$ value, known as the Chandrasekhar limit, in 1931, for which he was awarded the Nobel Prize in physics.

White dwarfs are dead stars, so they no longer produce energy by thermonuclear reactions. Rather, they glow from residual heat ($\sim 10^7$ K). As they age, though, their brightness and temperature fade, although it will take tens of billions of years to become completely dark (i.e., black dwarfs). In Fig. 4, a faint white dwarf can be seen in the center of the Ring Nebula.

Supernovae

The deaths of high-mass stars ($> 8\ \mathcal{M}_\odot$) occur quickly and violently via a supernovae explosion. These stars never have an electron degenerate core, and they continue to fuse higher atomic mass elements up to iron. However, an iron core presents two major dilemmas. First, up to this time, all of the nuclear reactions transformed lighter nuclei into heavier ones. In the process, energy was released because a small amount of mass was converted into energy. However, in order to fuse two iron nuclei, energy must be added to this reaction. But these stars need all of their released energy to support their tremendous masses. The second difficulty concerns the temperature in the iron core. The temperature reaches 5 billion degrees, and the photons produced in the nuclear reactions are gamma rays. Their energies are able to photodisintegrate an iron nucleus into about a dozen helium nuclei.

The iron core grows to roughly the size of the Earth and the mass of the Sun before these dilemmas are faced. Then, within a split second, the gamma rays photodisintegrate the entire core into helium particles, removing a tremendous amount of energy and pressure. The layers above the disintegrated core are no longer supported and rapidly collapse, traveling at close to one-tenth the speed of light. Electrons and protons are rammed into each other, creating neutrons and neutrinos. As the immense compression continues, the neutrons are pushed into a state of neutron degeneracy, where again, a quantum mechanical pressure prevents them from being squeezed any closer together.

Many collapsing layers of the supergiant star soon hit the rapidly developing neutron degenerate core. When these layers hit the degenerate core ''brick wall,'' there is a powerful rebound. The ensuring shock wave, aided with the pressure from the flood of recently created neutrinos, propagates outward through the dying supergiant. It tears open the star, creating the supernovae explosion. The sudden release of photons brightens the star to $10^{11}\ \mathcal{L}_\odot$. At its peak, a typical supernova is as bright as the galaxy within which it resides. As ejected stellar material is thrown into the interstellar medium, nuclear reactions continue. It is in these moments that most of the elements in the periodic table higher in mass than iron are created.

Observational studies indicate there are two general kinds of supernovae. Type I supernovae are discussed in the final section. The Type II supernovae are produced by the previously described scenario of the deaths of massive stars ($> 8\ \mathcal{M}_\odot$). The deaths of stars in the 4 to 8 $\mathcal{M}_\odot$ range currently pose a dilemma for stellar evolutionary theory. It was once thought these stars produced the Type Ia supernovae by a carbon–oxygen flash in their electron degenerate cores, an event that would certainly destroy the star. Currently, it is theorized that these stars experience a substantial mass-loss mechanism, reducing the total mass to a point that the carbon–oxygen core flash does not occur. Eventually these stars produce planetary nebulae and white dwarf remnants.

Neutron Stars and Pulsars

In 1967, radio astronomers discovered a peculiar object that was ''flashing'' with a very regular—and extremely short—period of 1.3373011 sec. Initially, the nature of this object was baffling, and some even suggested these were signals from extraterrestrial life! The rapid pulse rate dictated the source must be small and compact, so as not to fly apart. It was too fast to be a physically pulsating star, an eclipsing binary star system, or even a rapidly rotating white dwarf. Not until several months later, when more ''pulsars'' were detected, including one in the Crab Nebula (the remnant of a supernova explosion), was it realized that the theoretically proposed neutron star did in fact exist. The Crab Nebula is pictured in Fig. 5.

A neutron star produced by a Type II supernova explosion is about 1.5 $\mathcal{M}_\odot$ in mass, is approximately 30 km in diameter, and is in a state of neutron degeneracy. The mass contained in 1 cm^3 is 10^{11} kg or 200 billion tons! Neutron stars are similar to white dwarfs in that the diameter decreases as the mass increases. It is believed that neutron stars have an upper mass limit, but an exact value has been difficult to compute. Current thought puts the mass limit in the 2 to 3 $\mathcal{M}_\odot$ range. For objects greater than this limit, the final product is presumed to be a black hole.

The radio pulses are produced by the neutron star's immense magnetic field and incredible rapid rotation. The magnetic field of the presupernova star was once spread out over the surface of a supergiant, but now the surface area is extremely small, so the concentration of the magnetic field has risen by a factor of 10^{10}. The rapid rotation ($\sim$30 times/sec) is a natural consequence of the conservation of angular momentum, changing from that of a gigantic supergiant to a tiny neutron star. Because the magnetic poles are not coincident with the rotation axis, the rapid rotation acts like a giant electric generator. This creates a powerful electric field that pushes charged particles away from the neutron star. Because of the magnetic field, these particles quickly spiral along a curved path. This acceleration causes the charged particles to emit electromagnetic radiation. The radiation is confined by the magnetic fields to two ''beams'' that are projected

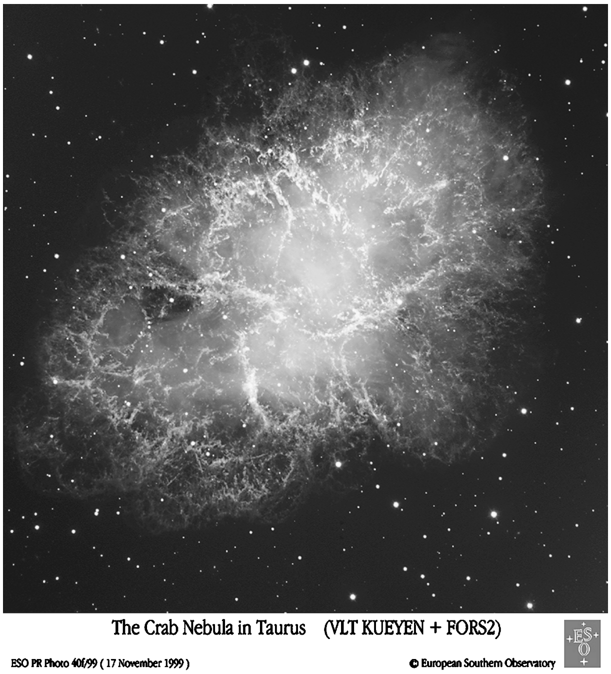

Fig. 5 The Crab Nebula was produced by a violent, supernova explosion. (Courtesy of the European Southern Observatory, photo ID: ESO PR Photo 40 f/99, November 17, 1999.)

from the neutron star. If one or both beams are pointed in our direction, the result is a periodic set of pulses, produced in a manner like that of a lighthouse beacon. Although much of the emitted radiation is in the radio wavelength region of the spectrum, pulses are detected at all wavelengths. The total energy (per second) in a beam is several thousand times that of the Sun's luminosity.

The pulsation rates range from over 4 to 0.0016 sec—the fastest one rotates more than 600 times/sec. Except for a few binary-star-system pulsars, they should gradually slow their rotation, lose their strong magnetic fields (due to the drag exerted on the beams), and fade from view. Currently about 700 pulsars have been detected, although it is believed that thousands more are in the galaxy.

Binary Stars with a Degenerate Component

When a white dwarf or neutron star is in a binary (double) star system having a very close companion, further events can occur in the star's life. When the companion star evolves toward either the red giant or supergiant phase, it may fill its Roche lobe. This ''surface'' is a figure-eight curve that defines where the gravitational pull from each star is equal. As the normal star continues to expand, some of its mass can be transferred to the other star. This material forms an accretion disk as it spirals toward and onto the small degenerate star.

A layer of hydrogen will build up on the surface of a hot white dwarf. The gravitational attraction of the white dwarf compresses the hydrogen layer, causing its temperature to increase. At about 10 million degrees, the hydrogen layer ignites in an explosive manner, for there are no overlying layers to regulate the nuclear reactions. The outer layers are blown off, and the burst of light is as bright as $10^5\ \mathcal{L}_\odot$. This peak intensity is maintained for a few days, but then the system declines back to its pre-outburst level. Such a brightening is called a nova, meaning a ''new'' star, because sometimes the peak luminosity would suddenly bring the object into naked-eye visibility. Novae can be recurrent, with the time interval usually being several decades.

If the degenerate component is a neutron star, the scenario is slightly different. The even higher surface gravities and temperatures of neutron stars quickly fuse some of the accreting hydrogen into helium, so there is a layer of hydrogen on top of a helium layer. Explosive helium burning releases a flood of X-ray photons, and these objects are called X-ray bursters. X-ray bursters can reoccur every few hours or days, depending upon the rate of mass transfer.

A final, catastrophic scenario involves the white dwarfs. If the accreting layer of hydrogen pushes the mass over the Chandrasekhar limit prior to igniting as a nova, then the white dwarf collapses. The collapse allows its nuclei to fuse explosively, resulting in a Type Ia supernova. These supernovae appear and behave differently than the Type II supernovae, produced by the death of massive stars. First, the Type Ia has no hydrogen in its spectrum. Second, its peak luminosity is about twice as bright as the Type II. And third, these objects are observed in all locations of all galaxies, whereas the Type II supernovae are found in the arms of spiral galaxies, which is the only location where massive, short-lived stars exist.

CONCLUSION

Stars experience a birth, life, and health. Although most stars have extremely similar composition, the total mass is the sole parameter that determines the type of death and the speed of evolution.

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