The 68th Compton Lecture Series

Stars: Their Life and Afterlife

Lecture 3: The Life and Times of Low Mass Stars

Brian Humensky, lecturer
http://kicp.uchicago.edu/~humensky/ComptonLectures.htm
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Part 1. Stellar Evolution on the Main Sequence

Stellar evolution is controlled primarily by a star's initial mass. A star's mass determines features like

- The surface temperature, luminosity, and radius.
- The main-sequence lifetime.
- The interior structure and dynamics, in particular how heat is transferred within the star, whether by radiation or by convection.
- The heaviest elements that can be synthesized by nuclear fusion in the core.
- The final state of the star: white dwarf, neutron star, or black hole.

Today we will talk primarily about low-mass stars, stars with masses < 4 M, and their evolution from the main sequence to the white dwarf phase. These light stars will either end their lives as red or white dwarfs or explode as Type Ia supernovae, leaving no compact remnant behind.

A star's life is all about trying to maintain hydrostatic equilibrium, or a balance between the force of gravity trying to contract the star and the pressure generated by the heat released in nuclear fusion in the star's interior. We saw with protostars that as they go through Kelvin-Helmholtz contraction and convert gravitational potential energy to heat, they are still unable to find equilibrium because KH contraction does not produce enough pressure in their cores to completely balance gravity: they continue to contract.

For stars with a mass greater than ~0.08 $M_{\odot}$, when KH contraction increases the core temperature to a few million degrees, hydrogen fusion begins and finally the star has a power source that produces enough internal pressure to counteract gravity. The star is now in hydrostatic equilibrium.

Hydrogen fusion into helium provides power to the star because it is "exothermic," meaning that free energy is released in the fusion reaction. Later in a star's life, if it is massive enough, we will see that it can fuse heavier atoms together as well (helium into carbon and oxygen, carbon into oxygen, neon, sodium, and magnesium, and so on) until iron is formed. However, at each subsequent stage, less free energy is produced. The free energy comes from the strong nuclear force, which holds neutrons and protons together in nuclei. However, the electric repulsion between the positively charged protons in a nucleus gets stronger and stronger as the number of protons increases. More and more energy is used to bind the protons together, leaving less available for release.

A tipping point is reached with iron, when the nature of the fusion reactions changes, becoming endothermic: extra energy needs to be added to cause two iron nuclei to fuse. A star cannot afford to lose energy during fusion, so it cannot fuse nuclei of iron or heavier elements. Instead, it builds up an inert core of iron during its final stages of evolution.

Below a mass of ~0.08 $M_\odot$, the temperature and pressure in the core never get high enough to initiate nuclear fusion. These "failed stars" are known as "brown dwarfs," and they continue to shrink and glow faintly via KH contraction for many years.

The Sun began its main-sequence life with a composition of

- 74% hydrogen
- 25% helium
- ~1% heavier elements, or "metals"

After ~4.6 billion years of burning hydrogen in its core, the Sun's core is now ~65% helium, but enough hydrogen remains for another 7 billion years of main-sequence burning. Outside of the core, the Sun's composition remains unchanged.

Stars are hottest in their cores and their material cools as one moves outward from the core to the surface. For stars similar to the Sun (with masses ~0.4-4.0 $M_\odot$), during their main-sequence lifetime they have a hydrogen-fusing core with a temperature of a few million degrees and a surface temperature of ~5-10 thousand degrees. How does the heat from the core propagate outward to the surface? The inner part of the interior, outside the core, is still hot enough that the gas is completely ionized. Ionized gas is essentially transparent, so heat from the core can radiate outward easily through the inner parts of the star. In the outer layers of the star, the temperature has dropped enough that the atoms are no longer completely ionized, and the gas becomes opaque. It catches the heat from the interior, and tries to confine it. However, much like a pot boiling, the lower parts of this opaque layer heat first and then rise in bubbles through the cooler surrounding gas. Thus, while radiation is used to transport heat in the inner layers of the star, convection is used to transport heat in the outer layers.

One important implication of this dynamical structure is that there is very little mixing between the hydrogen-burning core and the rest of the star for stars in this mass range. That means that once a star burns all the hydrogen in its core, it has no more fuel to burn (for a time) and falls out of hydrostatic equilibrium. The star will contract again, until the pressure and temperature in the core reach a point where helium can begin to burn.

As hydrogen turns to helium in the core of a star, the number of particles in the core drops, tending to lower the pressure. To maintain hydrostatic equilibrium over time, the core must contract slowly. Doing so boosts the pressure and temperature, increasing the rate of fusion reactions. A higher rate of fusion reactions means more energy is liberated per unit time, increasing the star's luminosity. The extra core pressure pushes on the outer layers of the star, causing it to expand. Over time, as the star's core turns hydrogen into helium, the surface of the star becomes larger and hotter.

Stars with a mass below ~0.4 $M_\odot$ are called "red dwarfs" because of the reddish color they take on due to their low surface temperature. Because light stars are much more likely to form than heavy stars, red dwarfs are quite common and make up about 85% of all stars. While the cores of these stars get hot enough to fusion hydrogen into helium, the gasses in the interior are not fully ionized. This means that the interior remains opaque, and heat from the core cannot be dissipated by radiation. Instead, these stars transport heat by convection. One implication of this is that the hydrogen in the outer layers is eventually mixed into the core, allowing red dwarfs, over the course of their lifetime, to burn all of their hydrogen into helium. Once the hydrogen is exhausted, red dwarfs could in principle burn helium, but they are too light to generate the temperature and pressure required. So, having run out of fuel, red dwarfs slowly radiate away their internal heat, shrinking and fading as they cool, much like brown dwarfs. Red dwarfs burn very slowly because of their low mass, so they have a lifetime of hundreds of billions of years. That is much longer than the age of the universe (13.7 billion years), so no red dwarfs have reached this stage of evolution yet.

Table 1. Properties and fusion products of stars as a function of their initial mass. Mass and Luminosity are measured relative to the solar mass.

Mass ($M_\odot$)	Surface Temp (K)	Spectral Class	Luminosity ($L_\odot$)	MS Lifetime (10^6 yrs)	Core Fusion Products
25	35,000	O	80,000	4	He, C, O, Ne, Na, Mg, Si, S-Fe, Ni
15	30,000	B	10,000	15	He, C, O, Ne, Na, Mg, Si, S-Fe, Ni
3	11,000	A	60	800	He, C, O
1.5	7,000	F	5	4,500	He, C, O
1.0	6,000	G	1	12,000	He, C, O
0.75	5,000	K	0.5	25,000	He, C, O
0.5	4,000	M	0.03	700,000	He

Part 2. Evolution after the Main Sequence

When a star with a mass greater than 0.4 $M_\odot$ exhausts the hydrogen in its core, the region just outside the core (now primarily made of helium) is hot enough to begin burning hydrogen. This is called *shell hydrogen fusion*. With the end of fusion in the core, the core begins to go through another round of Kelvin-Helmholtz contraction, converting gravitational potential energy into thermal energy. This energy heats the hydrogen-burning shell, increasing the rate of reactions there. Helium produced in the shell falls into the core, increasing its mass. Over several hundred million years of shell hydrogen fusion, the core condenses to about one-third of its original radius and its temperature rises from 15 million degrees to 100 million degrees. Figure 1 shows the evolution of a

Sun-like star's luminosity over time, beginning with the slow, steady rise during the main sequence and progressing – at this point – to the rapid rise at the end of the main sequence, when shell hydrogen fusion takes over.

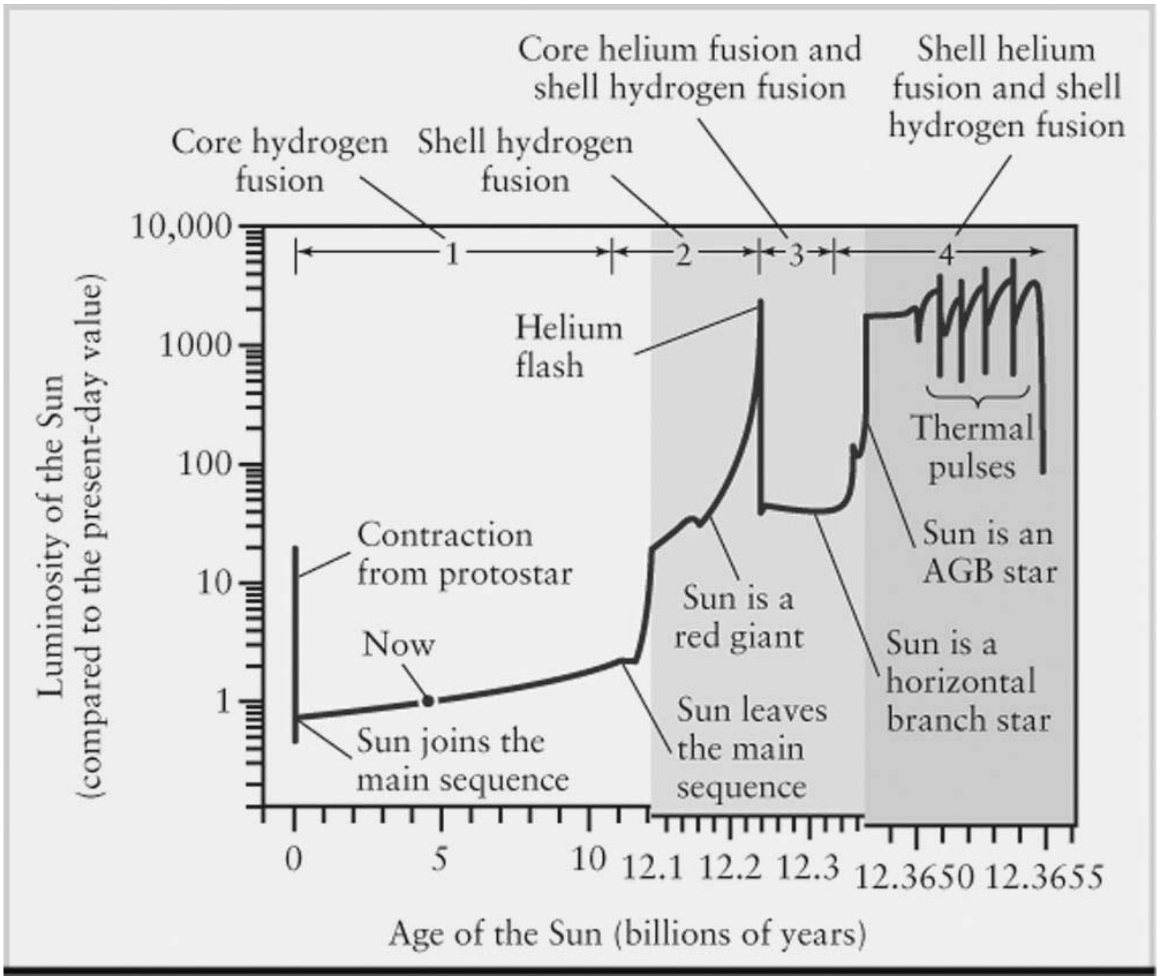
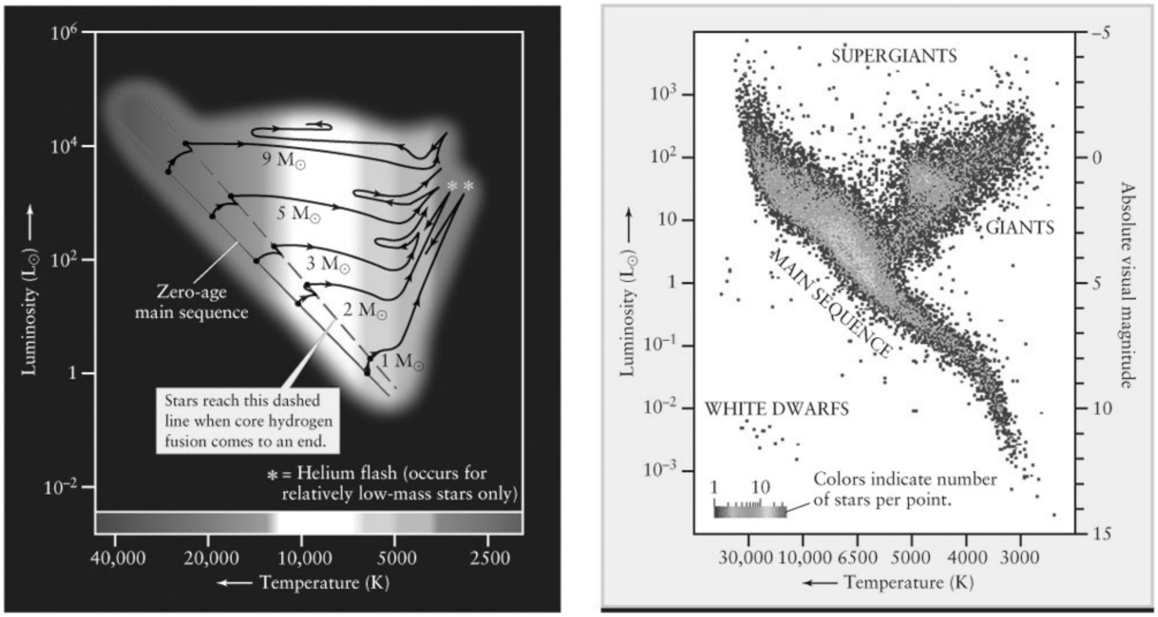


Figure 1. Luminosity versus time for a solar-mass star. Note the breaks in the X-axis: the post-main-sequence evolution takes place much more rapidly than the main-sequence evolution!

As the shell of burning hydrogen heats and expands to include more of the star's interior, the star's luminosity rises. The increased luminosity pushes on the star's outer layers, and they expand to many times their original size. As they expand, they cool to ~3500 K. The star is now a red giant. On a Hertzsprung-Russell (HR) diagram (see Figure 2), the star has moved up and right from the main sequence, towards higher luminosity and lower temperature, and into the region labeled "Giants."

Once the core's temperature reaches 100 million degrees, it is hot enough to begin fusing helium into heavier elements, carbon and oxygen. With helium burning supplying a new heat source in the core, the core temperature rises further and the core expands again. The hydrogen-burning shell is also forced to expand, causing it to cool and reducing the star’s luminosity. Lower luminosity means the outer layers will contract and heat up – the star moves back towards the lower-left on the HR diagram.



(a) Post-main-sequence evolutionary tracks of five stars with different mass (b) H-R diagram of 20,853 stars—note the width of the main sequence

Figure 2. Evolution of stellar luminosity and temperature on and beyond the main sequence.

Once the helium core is exhausted, history repeats itself and the star goes through a second red giant phase, in which helium burns in a shell surrounding an inert carbon/oxygen core. Initially an outer shell of hydrogen also burns; as the star expands and cools, the hydrogen burning will turn off. The star is so large in this phase that its outer layers are only weakly bound, and the star develops a strong wind that slowly blows these layers away.

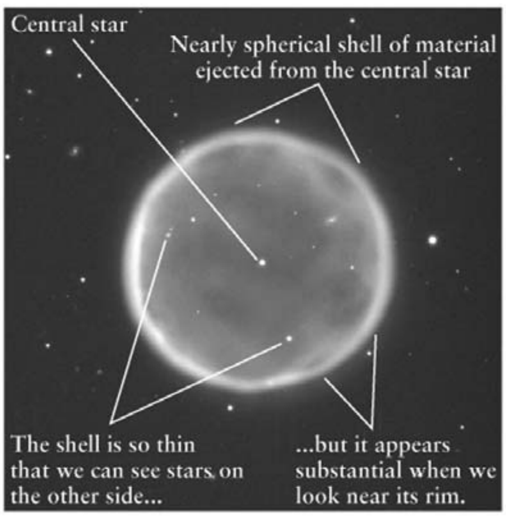
Lastly, the star enters a phase of “thermal pulses:” when the helium shell is exhausted, the star begins to contract and heat again, reigniting the hydrogen shell. As it burns, the helium it produces falls onto the helium shell. When the helium shell reaches a sufficient mass, it reignites with a flash and the star expands again, terminating hydrogen fusion. That flash, or thermal pulse, is intense enough to completely separate the star’s outer layers from its core. These layers expand and cool, and dust grains (micron-sized collections of molecules bound together) form. A series of these thermal pulses can strip a star completely of its outer layers, removing about half of its mass and exposing the hot core. Figure 3 shows two examples of planetary nebulae.

The outer layers, illuminated by intense UV light from the core and glowing via fluorescence, form “planetary nebulae.” These nebulae have nothing to do with planets – they were first observed in the 1800’s and resembled Jupiter-like planets when viewed with the telescopes available then. These nebulae expand at a rate of ~10 – 30 km/s, and after 50,000 years or so have spread far enough from the central star that they are no longer heated by it and fade out of view. Over time, the gases mix with the interstellar medium, enriching it in elements heavier than helium.

For a solar-mass star, here's a summary of its evolution:

- Core hydrogen fusion for 12 billion years (main sequence)
- Shell hydrogen fusion for 250 million years (red giant)
- Core helium and shell hydrogen fusion for 100 million years
- Shell helium and hydrogen fusion (2^{nd} red giant phase)
- White dwarf phase, fusion terminated

This series of stages is similar for all stars with initial masses in the range 0.4 – 4.0 $M_\odot$. More massive stars are able to reach high enough core temperatures and pressures to start fusion reactions involving carbon and oxygen. We will talk about these stars next week.



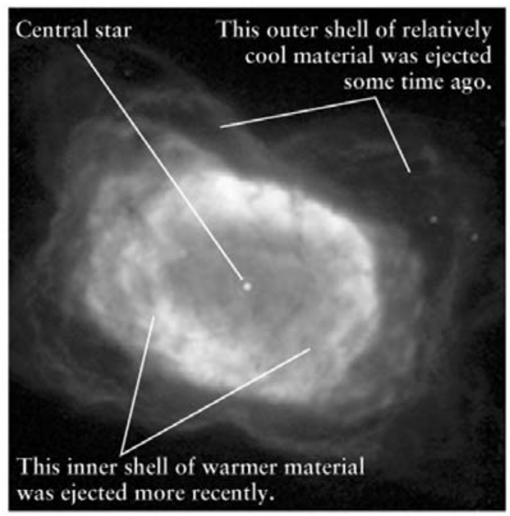


Figure 3. Examples of planetary nebulae. (left) Abell 39, 7000 light years away and 5 light years in diameter. (right) NGC 7027, 3000 light years away and 0.2 light years in diameter.

Part 3. End Times for White Dwarfs

As we saw above, stars with a mass in the range ~0.4-4.0 $M_\odot$ end their lives as white dwarfs, hot carbon-oxygen cores that have shed their outer layers of hydrogen and helium during their planetary nebula phase. White dwarfs are no longer powered by fusion, and they find balance against gravity in the pressure provided by their degenerate sea of electrons. They shine simply because they are hot. Left to its own devices, a white dwarf will slowly radiate away its heat, cooling and dimming into obscurity. After ~ 5 billion years as a white dwarf, the star's luminosity has dropped to $\sim 10^{-4}\ L_\odot$ and its temperature to ~4000 K. At this point, electrical forces between the constituent ions become important and cause the star's material to form into a regular lattice – the white dwarf essentially freezes into a solid.

White dwarfs have a mass of ~1.2 $M_{\odot}$ or less. This limit is imposed by two conditions. First, if the mass were much greater than this, the gravitational force would be able to overcome the electron degeneracy pressure, and the star would contract and heat to the point where further fusion – and evolution – were possible. Second, at about this mass a process called "neutronization" becomes possible: the most energetic electrons in the gas would have enough energy to bind with protons and form neutrons and neutron-rich nuclei. The loss of free electrons means a lower pressure, and again the star is forced by gravity to contract in response.

The story is quite different, however, for white dwarfs in close binary systems. If a white dwarf is in a binary system with another star that is near enough, matter can transfer between the two stars. In some cases, an accretion disk can form around the white dwarf, and matter can steadily be added to the white dwarf's surface. What happens next appears to be related to the rate of accretion, but the details remain unclear.

Novae appear to occur when a white dwarf acquires hydrogen-rich matter from its companion at a very slow rate. A surface layer of hydrogen forms, compresses, and heats. When the temperature reaches about 10 million degrees, hydrogen fusion ignites throughout this surface layer, and this surface explosion is what we see as a nova. Novae have an energy of ~10^{37} joules (10^{44} ergs), which is equivalent to the output of our Sun over 1000 years. The white dwarf and its companion survive the nova explosion, and in some cases repeated novae are possible!

Type Ia supernovae appear to be initiated by a similar mechanism, but the details are still being worked out. In a Type Ia supernova, the explosion begins with carbon fusion in the core of the white dwarf, but it is not clear what begins the carbon fusion. Possibly it is a launched by explosive burning of a helium surface layer that sends a shock wave through the star, compressing the core, or possibly a sufficiently high accretion rate increases the mass of the star to a point where the core's pressure becomes high enough to start carbon fusion.

Carbon fusion raises the temperature in the core, but because the core is being supported by electron degeneracy, the increased temperature does NOT cause the core to expand! Instead, the increased temperature causes the fusion rate to accelerate, and this positive feedback causes the fusion process to run away. The fusion reaction spreads rapidly from the center of the star, and within seconds the white dwarf blows apart. These explosions are far more energetic than novae, releasing ~10^{44} joules (10^{51} ergs) of energy, comparable to the amount the Sun will emit in its entire main-sequence lifetime.

Coming Up Next Week: The Life and Times of Massive Stars

Next week we'll cover the continuing evolution of massive stars, and take a look at SN1987A as a very well studied example.

References

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Salaris, M. and Cassisi, S. Evolution of Stars and Stellar Populations (2005)

Credits for Figures

Figure 1: Reproduction of Figure 19.9 from Freedman and Kaufmann.

Figure 2: Reproduction of Figure 20.5 from Freedman and Kaufmann.

Figure 3: Reproduction of Figure 20.6 from Freedman and Kaufmann.