27. The History of a Star

Stars have always fascinated humans. We can hardly be outside on a clear night without being overwhelmed by a feeling of awe when contemplating the beauty and majesty of the heavens. Our earliest attempts at science involved possible explanations for the orderliness that could be observed even without sophisticated instruments. As we have come to understand our universe better, it has continued to fascinate us with an unending chain of surprises.

This chapter will describe the history of individual stars, beginning with their formation from interstellar “dust” to the time when they no longer emit light. We will not attempt to outline the evidence for this picture of stellar history, but will simply relate the story as it is now understood.

We will begin by describing the history of a star that has about the same mass as the sun. Those with more mass or less mass will go through the same formation process, but the time scale will be different. Later, we will also describe the “old age” of more massive stars.

From Dust to Star in 10 Million Years

All of space contains matter. Even the “emptiness” of the space between galaxies has about one atom per cubic meter. About 75 percent of the mass of the universe appears as hydrogen, with helium making up almost all of the balance.

Galaxies contain large regions where this interstellar matter is considerably more dense, with perhaps a million or so atoms per cubic meter. These immense “dust” clouds are the formation grounds for stars (Color Plate 6 and book cover). A million atoms per cubic meter sounds like a lot, but the density in these clouds is still many, many times lower than in the best vacuum available on earth. By comparison, ordinary hydrogen gas at atmospheric pressure contains $10^{25}$ atoms per cubic meter. $10^{25}$ is the approximate number of grains of sand on all the beaches on the whole earth. A million grains would be a mere handful.

Temperatures within these interstellar dust clouds are about $-150$ °Celsius. Even so, the atoms are moving at a high speed, about 1.5 kilometers/second (3,300 miles/hour). They collide with each other occasionally, but they are basically free particles in space, moving independently of one another in random directions.

Occasionally, these random motions occur in such a way that a large collection of atoms forms a “pocket” in which the density is about 500 times the average. If the pocket is large enough (about 15 trillion kilometers in diameter, or 1000 times larger than the solar system), the atoms are held together by their mutual gravitational attraction. This accidental accumulation of matter is the beginning of a new star—a protostar.

Each atom of the protostar is attracted to each other atom by the gravitational interaction. All these interactions result in each atom experiencing a net force whose direction is toward the center of the protostar. The atoms “fall” together under the influence of these forces. As they fall, they lose gravitational potential energy and gain kinetic energy, moving faster and faster as they get closer together.

As the atoms move faster and closer together, they collide more often with each other. Their kinetic energy becomes “thermalized,” and the temperature of the collection increases. The protostar shrinks in about three million years (a mere twinkling of an eye on a cosmic time scale) to a ball about the size of the earth’s orbit. Its interior temperature rise to about 50,000°C, and its atoms move at about 35 kilometers/second. The gas is still quite diffuse (about 1 percent of the density of hydrogen gas at atmospheric pressure), but important things are happening that affect the future course of events.

For one thing, these high-speed particles in the interior of the protostar exert considerable outward pressure on the outer layers. This slows their collapse so that it will take another 10 million years to reach a size only about twice that of the sun. In fact the rest of the star’s history is governed by the interplay between these two effects: the inward pull of gravity versus the outward pressure resulting from the thermal motion of the star’s interior (Fig. 27.1).

The second important development, which occurs at about this time, is that the atoms become totally ionized. The collisions at these temperatures are so vigorous that the electrons are removed from the atoms, leaving atomic nuclei (mainly protons) and helium nuclei as free particles in the interior of the protostar; the gas
becomes a plasma contained by the gravitational force. Finally, this large cloud of ionized gas becomes visible. It begins to emit electromagnetic radiation as the charged particles are accelerated during their thermal collisions in the same way an incandescent lightbulb or an electric hot plate does. The charged particles are accelerated by thermal agitation and accelerating charged particles always emit electromagnetic radiation.

The emission of light through the electromagnetic interaction constitutes a significant loss of energy for the emerging star, and the protostar subsequently collapses (Fig. 27.2). The energy lost by the emission of light reduces the temperature and, hence, the pressure of the interior. With reduced pressure, the gravitational force exceeds the outward pressure, and the protostar collapses further. The collapse causes a loss in gravitational potential energy because it is converted, as before, to thermal energy. This raises the temperature, and, therefore, the pressure of the interior. The increased pressure then balances the inward gravitational force and halts the collapse. But energy is still being lost by radiation, so this sequence of events repeats itself over and over, with the protostar becoming smaller and smaller as its gravitational potential energy is converted first to thermal energy and then to radiation. These processes continue for about 10 million years until the protostar has shrunk to a size about twice that of the sun, and with an interior temperature of about 10 million degrees. However, at this point you would still not call the protostar a star. The nuclear furnaces that will govern most of its life have not yet started.

**From Youth to Maturity in Another 17 Million Years**

When the internal temperature of the protostar reaches about 10 million degrees, a new process begins that will govern the dynamics of the star throughout the remainder of its active life: nuclear fusion. Nuclear collisions at these temperatures are violent enough that the positively charged nuclei come together within range of the strong force. The nuclear force can and does become important.

We will not describe the nuclear reactions in detail, but the principal result is that four protons combine to form a helium nucleus. Two positrons and two neutrinos are also emitted for each helium nucleus that is formed, and there is a significant reduction in nuclear potential energy. This is released as kinetic energy and neutrino energy. The kinetic energy is quickly distributed among the particles that make up the star, raising the temperature and pressure of the stellar interior. This source of energy regulates the size of the star as it reaches a balance between inward gravitational pull and outward pressure.

The new star continues to contract slightly for about 17 million years (a small fraction of its total life) until its interior temperature rises to about 30 million degrees and its radius approaches that of the sun. At this point, the energy released by the nuclear reactions balances the energy lost by radiation of light and neutrinos. The interior pressure is sufficient to balance the inward pull of gravity. The star settles down to a middle age that will probably last another 10 billion years or so.

**An Adult Life of 10 Billion Years**

A star spends most of its life in this mature state of equilibrium, which is the state we most often see. Each star is a seething cauldron of activity, but the balances of energy and pressure cause it to seem much the same year after year. However, the seeds of its demise are being formed deep inside the star, even from the instant when the nuclear furnaces are first ignited.
As protons combine to form helium nuclei, the proton “fuel” is gradually consumed. The ratio of hydrogen to helium is gradually reduced, and the fraction of nucleons bound into helium is gradually increasing. Soon (after 10 billion years or so) there will not be enough protons to keep the nuclear reactions going. The release of nuclear energy will slow down and stop, the temperature and pressure of the stellar interior will drop, and the inexorable gravitational force will cause further collapse of the star. In the meantime, the star stabilizes with an interior temperature of about 30 million degrees and a surface temperature of about 5500°C.

Incidentally, we never see light directly from the star’s interior because it is absorbed by the star’s outer layers. The light emitted by the star comes from these comparatively cooler layers. The nuclear reactions only take place in the high-temperature center of the star, a region that contains about one-fiftieth of the star’s total volume.

The actual adult lifetime of a star depends on an unexpected way on the star’s mass. Stars with the most mass have the shortest lives because higher interior pressure and temperature are required to balance the gravitational compression associated with greater mass. The rates of the nuclear fusion reactions increase rapidly with temperature, so the larger stars fuse hydrogen to helium at a much higher rate than do stars with less mass. The larger stars have more to begin with, but the overall effect is that more massive stars use up their nuclear fuel sooner than their less massive cousins. This effect is so important that a star with ten times as much mass as the sun would live only about 100 million years (100 times shorter than the sun). On the other hand, a star with only one-tenth the mass of the sun would live 100 times longer to a ripe old age of about a trillion years.

The Star Becomes a Red Giant

As the nuclear hydrogen fuel in the center of the star is used up, the hydrogen fusion region expands outward, leaving behind a central core of helium in which no nuclear reactions take place. This greatly increases the region of high temperatures and, for the first time since the collapse began, the pressure outside the hydrogen-burning region exceeds the inward gravitational pressure, and the star expands to about 50 times its normal size in 100 million years or so. As it expands, its outer layers become cooler. Its color becomes redder, more like an electric hot plate or stove filament than an incandescent lamp. During this stage the star is called a red giant (Fig. 27.3).

Meanwhile, the helium core continues to contract under the influence of gravity. (Remember that there are now no nuclear fusion reactions in this region of the star to prevent the collapse.) Its temperature increases to approximately 200 million degrees, which is necessary to initiate the fusion of helium to carbon. This new energy source increases so rapidly that the entire nuclear furnace, both hydrogen- and helium-fusion regions, explodes inside the red giant. These regions then become so diffuse that all the fusion reactions stop.

With its nuclear furnaces not operating, the star quickly cools and collapses back to its original size in a mere 10,000 years or so. As the star collapses it experiences a familiar sequence of events: gravitational potential energy is converted to thermal energy, and the temperature of the star’s interior begins to rise. However, this time hydrogen fusion does not stop the collapse because the star is mostly helium. The collapse continues until the interior is again at 200 million degrees, at which point helium fusion begins for the second time. Once again the star is in equilibrium where it remains until enough carbon accumulates in the center so that the helium fusion moves outward.

Depending on its mass, the star may go through one or more red-giant stages much like the one described above. Each time, the nuclei become more massive than before until, ultimately the nuclear particles reach their minimum potential energy. Eventually the nuclear furnaces all go out, and the star is left without an internal source of energy. Each successive expansion and contraction occurs in a shorter and shorter time, so that the nuclear furnaces go out only a few million years after helium fusion first begins.

Death of a Small Star

Small stars with masses similar to that of the sun will not proceed further than the helium-burning stage. As the helium moves away from the center of the star, changes in the outer layers cause these to be “blown” away as if by a gigantic explosion. These leave the star displaying a planetary nebula, one of the prettiest sights seen through a telescope (Color Plate 7).

When the outer layers of the star are gone, the core remains as a white-hot, but small, sphere with a central region composed mainly of carbon nuclei, a larger layer
in which helium fusion is still occurring, and an outer layer in which no nuclear fusion is taking place. At this point the star is almost as small as the earth and is known as a white dwarf.

Nuclear fusion gradually stops as helium is used up. The white dwarf is a collection of hydrogen, helium, and carbon nuclei together with enough electrons so that the whole is electrically neutral. It continues to collapse until the electrical repulsion of the particles balances the inward gravitational force. As the nuclear fusion diminishes, the white dwarf gradually cools for a very long time until it no longer emits light. It has become a black dwarf, a mere cinder in space. Its density, however, is extremely high. After all, it is an object about the size of the earth with a mass near that of the sun. One cubic inch of such material would weigh 10 tons near the earth! The surface gravity near a white or black dwarf is about a million times that on earth.

Death of Massive Stars

Massive stars (those with masses several times that of the sun) proceed to a somewhat different end. After their hydrogen and helium fuels are expended, they collapse gravitationally until their central temperatures are about 600 million degrees Celsius. At this point, carbon fusion begins to form more massive nuclei. A new cycle of fuel consumption, expansion, and contraction begins. Such processes may continue until nuclei with masses near iron are formed. However, the iron nucleus is the most tightly bound of the nuclei, and further fusion can only occur at the expense of the free kinetic energy of the pieces being fused. With the formation of iron, the fusion fire cannot free additional nuclear potential energy to sustain itself. The “fire” at the center of the star goes out. The core collapses and then rebounds, sending a shock wave outward toward the surface of the star. The compression of the shock wave generates great heat. A conflagration (supernova) occurs in which nuclei beyond iron in the Periodic Table are formed and hurled out into space to become the material of succeeding generations of stars such as our own sun (Color Plate 8). At the center a neutron star is formed.

Even if the mass of the remnant is no more than a few times the mass of the sun, the reduced size of the object nevertheless creates gravitational forces that are strong enough to force a combination of electrons and protons in the matter to form neutrons. In many respects the resulting object is like a giant nucleus, although it contains several times the mass of the sun. The density is such that a pinhead-size ball of such matter would weigh in the region of a billion tons if it could be brought to the surface of the earth.

Neutron stars (about 10 miles in diameter) are much too small to be seen directly through a telescope. But astronomers do see objects which they call pulsars—objects observed as very precisely timed bursts of radio waves and x-rays that flash periodically from a very compact region of the sky. They have long been thought of as rapidly spinning neutron stars. The neutron stars have super-strong magnetic fields that cause charged particles to accelerate and emit the radiation.

Neutron stars are thought to be the end product of a supernova explosion. Supernovae were observed with the naked eye in the years 1054, 1572, and 1604. The supernova of 1054 (reported by Chinese astronomers) occurred in the sky where astronomers now see a rapidly expanding cloud (the Crab Nebula, Color Plate 8) and where x-ray astronomers see a pulsar that flashes every 0.033 second. Supernovae often occur in other galaxies but are usually only visible by telescope and are so distant they are difficult to study in detail.

For the first time since 1604, astronomers in 1987 were exposed to a supernova visible to the naked eye in the southern hemisphere. But for the first time in history the astronomers had telescopes and neutrino detectors to study the exploding star. Theory predicts a neutrino burst as the red-giant star collapses and explodes. The neutrino burst was seen by several detectors on earth, but a check of star maps revealed that before exploding the star was a very large, bluish star (a “blue giant”) rather than a red giant. This unexpected detail can rather easily be accommodated by theory. The pulsar, if one is actually there, is apparently not detectable.

Black holes are even more massive and more exotic than neutron stars. It was one of the crucial tests of General Relativity to observe the bending of the path of light from a star as it passed the sun on its way to earth (Fig. 27.4). The bending of light for a star with as small a mass as our sun is slight. Imagine light emerging from a star as in Figure 27.5. As the star collapses, its surface gravity increases and the path of emerging light is more severely bent until the cone of emission eventually closes and no light can escape. Using our analogy of the rubber sheet in Chapter 26, it is as if the spacetime region is

![Figure 27.4. A two-dimensional analogy of the way massive objects give rise to curvature in spacetime. Light bending near the surface of the sun (greatly exaggerated in the diagram) was crucial evidence for Einstein’s General Theory of Relativity.](image-url)
pinched off and goes out of existence (Fig. 27.6).

We don’t know of any force that can halt the collapse of a black hole down to a point. Indeed, if a mechanism to halt the collapse is imagined, it invariably requires adding additional mass-energy to the system to exert the force—and this only aggravates the collapse. Thus, in theory, if a body of mass is compressed within a critical radius, the subsequent collapse is inevitable.

Black holes are also too small to be seen directly, but, in principle, we can see matter in the space just outside the black hole. The gravitational fields surrounding a black hole are extremely intense. In those instances where another star is orbiting a black hole, gas may be pulled from the other star into the black hole. The process is so violent that an enormous amount of energy as electromagnetic radiation is emitted in the radio and x-ray regions of the spectrum. Very intense emitters, including objects called quasars, are observed by astronomers, and these are modeled fairly well by black holes. There are simply no other credible explanations at present for such objects. Black holes may have only a few solar masses, but supermassive black holes may contain from one million to ten billion solar masses and the region immediately surrounding them may exceed the brightness of rather bright galaxies by factors ranging from 100 to 1000.

A modest (million solar masses) black hole is also thought to be at the center of our own galaxy where it accretes gas, dust, and entire stars from the galaxy’s central regions. We can tentatively say that black holes have been (indirectly) observed to the extent that black holes are inevitable in theory and no credible alternative explanations have yet been found for some x-ray emitters, for quasars, and for the core of our galaxy.

Summary

Rather than being unchanging and everlasting, stars are formed from elemental materials in the universe and proceed through a predictable cycle of events. Each star begins as a collection of atoms attracted to each other by gravity. As the atoms fall toward each other, they gain kinetic energy that in turn becomes thermal energy. This finally makes the star a star. Its history is determined by the balance or imbalance of the inexorable inward gravitational pull and the outward pressure of its high-temperature interior. All of the fundamental interactions (forces) are involved in the complex sequence of events.

Most stars, after emitting as much energy as is available, end their visible existence as white dwarfs and then become black dwarfs, intensely dense but non-luminous collections of matter. Stars with more mass may become spectacular supernovas before reducing themselves to neutron stars. The most massive stars are thought to become black holes in which gravity is so strong that light itself cannot escape (Fig. 27.7).
Historical Perspectives

Pericles, the leader of Athens at its most glorious period, brought Anaxagoras (488-484 B.C.) to Athens to add to the cultural life of the city. However, Anaxagoras held the unorthodox view that the sun was a giant, red-hot stone that was about the size of Greece. He also thought that the moon shone by reflected light and had mountains as well as inhabitants, views which denied the divinity of the moon. His impiety landed him in enough trouble that he had to be rescued by his patron.

But even then people were thinking about the sun and the stars and wondering what they were. Democritus (ca. 400 B.C.), who invented the atom, also proposed a long time before the telescope was invented that the Milky Way consisted of unresolvable stars. Of course, Galileo confirmed that view when he turned his new telescope on the heavens in 1610. By the 17th century it was a quite widely held view that each of the “innumerable stars” in the infinite void were the suns of planetary systems like our own.

Aristarchus of Samos (ca. 310-230 B.C.) was one of the scholars at the great Library of Alexandria. He was probably the first person who believed that the earth, with the other planets, moved about the sun. From the size of the earth’s shadow on the moon during a lunar eclipse, he concluded that the sun was several times larger than the earth and that it was 19 times more distant than the moon. But it was an idea whose time had not come; it would be 1800 more years before Copernicus in 1543 would revive and confirm the idea. Meanwhile, Cleanthes, head of the Stoic school of philosophy, thought that Aristarchus ought to be indicted for impiety.

In 1750 Thomas Wright (1711-1786) wondered if the stars themselves formed a system just as the planets form a solar system around the sun. He imagined the Milky Way as such a system moving around a governing body at the center. In 1755, German philosopher Immanuel Kant (1724-1804) expanded on Wright’s system by speculating on the nebulae. The small white nebulae were objects that the telescopes revealed to be diffuse, cloudlike objects apparently sitting among the pointlike stars. Kant conjectured that these, like the Milky Way, were vast systems of stars. In this view, these “island universes” all revolved around a common center.

William Herschel (1738-1822) was a German who went to England and became a musician in the Hanoverian Guards, while also being an expert telescope maker who both sold and used the instruments he made. Eventually he caught the attention of King George III and became the king’s astronomer. His careful observations revealed clusterings of stars, which he interpreted to give the disklike shape of the Milky Way with our solar system at the center. He believed that beneath its fiery exterior the sun had a cool, solid surface suitable for its inhabitants! The view that the sun, moon, and planets were inhabited was not uncommon in the early 1800s, but it declined by the end of the century as more evidence of the inhospitable environments of these places was accumulated.

But what were the stars? Even with a telescope the stars appear to be points of light. Probably the single most important innovation after the telescope itself came in 1823 when Josef Fraunhofer used a prism at the focus of a telescope to break the light of a star into its spectrum of colors. What he observed were the black lines of an absorption spectrum (see Chapter 15), which gave the first evidence for the actual composition of the stars. Fraunhofer and his successors developed methods to tell what elements were present in the surface of the star (from comparisons with laboratory spectra), the temperature and pressure of the environment producing the spectra (from the laws of thermodynamics as they apply to the excitation and ionization of atoms), the translational and rotational motions of the star (from the Doppler shifts), and the presence or absence of magnetic fields—all this from the light emitted by atoms on the surface.

However, the sun was still a puzzle. It was emitting unbelievable amounts of energy. William Thomson (Lord Kelvin) entered the evolution controversy after the appearance of Darwin’s theory in 1859, arguing that
the sun, with then-known sources of energy, could sustain its current luminosity for at most 30 million years. This amount of time was much less than the supporters of evolution thought necessary for their interpretation of things. Thomson’s reputation was sufficient that he could not easily be discounted, and a very lively debate ensued until the end of the 19th century. It was not until 1938 that Hans Bethe would develop the model based on the fusion of hydrogen into helium that we use today. The fusion model is more complex than we have indicated in this chapter and could not be developed until accurate measurements could be made of the probabilities of a number of nuclear reactions. The model at last allowed astrophysicists to compute self-consistent models of the sun and stars in which nuclear energy release in the core compensates for the loss of energy through surface luminosity.

STUDY GUIDE  
Chapter 27: The History of a Star

A. FUNDAMENTAL PRINCIPLES

B. MODELS, IDEAS, QUESTIONS, OR APPLICATIONS
1. Where are stars “born”?  
2. What occurs during the protostar phase? Why?  
3. What occurs during the mature phase of a star? Why?  
4. What occurs during the red-giant phase of a star? Why?  
5. What occurs during “old age” and the “death” of a star with small mass?  
6. What occurs during “old age” and the “death” of a more massive star?  
7. What occurs during “old age” and the “death” of a very massive star?  

C. GLOSSARY
1. Black Dwarf: The nonluminous end state resulting from the death of a white dwarf.  
2. Black Hole: A gravitationally collapsed object of such great density that ordinary radiations, such as light, cannot escape from within, but which nevertheless produces great amounts of radiation from the accelerated matter that surrounds the black hole.  
3. Dust Cloud: Within a galaxy, vast regions of matter in the form of dust, gas, and plasma.  
4. Mature Star: A star in the very long-lived stage of its existence when it is fusing hydrogen into helium.  
5. Neutron Star: The model of a pulsar which accounts for its radiation being emitted from a rapidly spinning object of small size (a few miles in diameter) made of very dense nuclear matter (mostly neutrons).  
6. Planetary Nebula: A halo of material that has been thrown off an exploding star that is going into its white dwarf stage.  
7. Protostar: A collapsing dust cloud, pulled in on itself by gravity, that has not yet reached the temperature at its core that is required to ignite fusion. The earliest stage in the formation of a star.  
8. Quasars: Literally, quasi-stellar radio sources. Very intense emitters of electromagnetic radiation, the quasars are yet unexplained objects that are thought to be very distant, primitive structures of the early universe.  
9. Red Giant: A large, relatively cool (reddish) star with a collapsing center and an expanding outer shell. The red-giant phase is a later stage in the lifetime of a star that occurs when fusion subsides at the center (resulting in collapse at the center) but otherwise spreads outward from the core (causing an expanding outer shell).  
10. Supernova: The cataclysmic explosion that marks the death of a star of relatively large mass (several times the mass of our sun) which has reached the iron limit in fusion.  
11. White Dwarf: A very hot, white star of relatively modest mass (comparable to the mass of our sun) that is incapable of igniting the fusion processes that lead to the heavier elements and will therefore die once its current hydrogen and helium fusing processes are exhausted.

D. FOCUS QUESTIONS
1. For the three categories of stars listed below:
   a. Name and state the fundamental principles that govern the history of the star (see Section A above).  
   b. In terms of these principles, describe each phase of the history of the star from “birth” to “death”.  
      1) The least massive stars, including stars like our sun.  
      2) Stars with three to five times the mass of our sun.  
      3) The most massive stars.

E. EXERCISES
27.1. What forces cause the particles making up a protostar to collapse?  

27.2. Why does the temperature of a protostar increase as the protostar gets smaller?
27.3. Why does a protostar emit light? Where does the energy come from, and how is it converted to light?

27.4. Why do protostars of large mass contract to stars more rapidly than those with less mass?

27.5. Why does a protostar become smaller as it emits light?

27.6. Why does a star stop collapsing when its internal temperature first reaches about 10 million degrees?

27.7. Why does a star emit light? Where does the energy come from, and how is it converted to light?

27.8. Describe the balance of forces that stabilizes the size of a star during its hydrogen fusion stage.

27.9. Describe the balance of energy that occurs during the hydrogen fusion stage of a star.

27.10. Why is energy released when hydrogen nuclei combine to form helium nuclei?

27.11. Why does a very massive star complete its hydrogen-burning phase more rapidly than a less massive star?

27.12. What source causes a star to expand and become a red giant?

27.13. Why does the surface of a star cool as it expands to become a red giant?

27.14. Why is a red giant red?

27.15. The helium nuclei formed during the hydrogen-fusion phase collect near the center of the star. Why would this be expected to occur?

27.16. Why does it require a higher temperature for helium fusion in a star than it does for hydrogen fusion?

27.17. Why do the “nuclear fires” go out in smaller stars after helium burning but continue in larger stars until iron nuclei are formed?

27.18. Why is the surface gravity of a white dwarf so high?

27.19. Why do more massive stars eventually become neutron stars, while less massive ones do not?

27.20. What is a “white dwarf”? Why is a white dwarf white?

27.21. Why does a white dwarf gradually cool and eventually become a black dwarf?

27.22. What is a “black hole”? Why is a black hole black?

27.23. What is the difference between a neutron star, a white dwarf, and a black hole?

27.24. The planet Jupiter seems to be made mostly of hydrogen. Why isn’t Jupiter a star?

27.25. Where do the heavy elements in the earth’s crust come from?

27.26. What observed objects are modeled as neutron stars?

27.27. What observed objects are modeled as black holes? What evidence leads us to believe black holes actually exist?

27.28. Pick the following set of star name, energy source, size, and lifetime that are consistent.
   (a) protostar, gravity, small, long
   (b) normal, H, medium, short
   (c) red giant, C, large, short
   (d) normal, He, medium, long
   (e) white dwarf, He, small, long

27.29. A black hole was once a star with mass
   (a) equal to that of sun.
   (b) a small fraction that of sun.
   (c) about 90 percent that of sun.
   (d) many times that of sun.
   (e) about twice that of sun.