Stellar Death

The Inexorable Grip of Gravity

1. Red Giants

The Sun looks the same to us, unchanging, day after day. A simple observation, however, tells us that it is evolving and must be changing in some manner. That observation is just the warmth on our upturned faces on a sunny day. The radiation that flows from the Sun carries energy out into space. There is nothing from space replacing that energy. The Sun must, therefore, be losing energy overall. Something must be going on within the Sun that is slowly, inevitably altering it. The lesson from Chapter 1 is that the change in the Sun involves its composition. The Sun is irrevocably transmuting some of its hydrogen into helium. That transformation cannot be undone. The alteration of the structure of the Sun is slow, but it is steady. Eventually, the changes will be drastic.

As remarked in Chapter 1, the hydrogen burns only in the center of a star, where the temperatures are highest. That means that the central region is where the hydrogen is consumed and the helium builds up. Even when the hydrogen is fully transformed in the central region, the outer, cooler portions of the star will not have burned. They retain their original composition. This causes the star to become schizoid and to do two things simultaneously: shrink and swell. This development is in strict accord with the principle of conservation of energy, but the application of this principle is more complex than for stars with a homogeneous composition.

When hydrogen is exhausted in the center, the star has a central volume of nearly pure helium (along with the scattering of heavy elements initially present in the star). The remainder of the star is original material, composed mostly of hydrogen. The difference between the inner parts of the star where the composition has been altered and the outer part where the composition is unchanged become ever more distinct as the star evolves. To distinguish these two portions of the star, the inner part is called the *core*, and the outer part, the *envelope*.

The helium in the stellar core can become a thermonuclear fuel. Helium burning does not happen spontaneously, however, any more than hydrogen burning did. The nuclear force is strong, but it only acts over very short distances. The particles to be combined must be brought close together. There is, however, a force that inhibits the particles from getting close to one another. This is just the electrical force of the repulsion of like charges. The nuclei of atoms, such as hydrogen, helium, or heavier elements, are composed of positively charged protons and neutrons with no electrical charge. All nuclei thus have a net positive charge. If the electromagnetic force and gravity were the only forces in the Universe, this charge repulsion would prevail, and there would never be any nuclear reactions.

To initiate thermonuclear burning, the charge repulsion among the protons must be overcome. The electrical repulsion is not as strong as the nuclear force, but it acts over greater distances and dominates while the particles are far apart. At close distances, the nuclear force is stronger, and it can grab the particles and bind them tightly together. To bring like-charged particles together so the nuclear force can grab them and liberate energy, some energy must first be expended to fling the particles together despite the resistance of the electrical repulsion. You do not get something for nothing, but the nuclear payoff is worth the investment of some energy to overcome the charge repulsion. This principle is illustrated in Figure 2.1.

In practice, the charge repulsion is overcome by investing the particles with heat energy. This gives them more random energy of motion so they collide more fiercely and come closer within the grasp of the nuclear force during an encounter. To burn a nuclear fuel, you have to heat it first by raising the temperature, just as you need a match and kindling for the wood in a fireplace. A protostar must contract sufficiently to heat the hydrogen to get burning started initially. Helium nuclei have two protons, whereas hydrogen nuclei have only one. The charge repulsion is stronger for helium than for hydrogen, so helium must be heated to higher temperatures than hydrogen before it undergoes thermonuclear reactions.

When the last of the hydrogen burns out in the center of a star, the star must get even hotter to burn helium. It solves this problem in a natural way, using energy conservation. After the hydrogen burns out in the center, no energy is being produced. Without the input of heat, the pressure cannot support the star. The star thus contracts and derives heat that way until the helium becomes hot enough to burn. The same mechanism that is responsible for igniting and regulating hydrogen burning on the main sequence causes the helium to ignite after the hydrogen is exhausted in the center. When the star has insufficient heat, it naturally contracts until that heat can be provided, whether by hydrogen, helium, or ultimately other sources of nuclear fuel.

Now comes the schizophrenia. The helium core contracts and heats until helium ignites. In its inimitable way, the gravitational contraction liberates more heat energy in the core than the core needs. The excess heat flows out into the overlying envelope of pristine material. The envelope responds in its own natural, but opposite, way. The envelope feels that it is getting an excess input of heat. The excess pressure causes the envelope to expand against gravity and cool to lower temperatures. The star thus does both things at once. The core loses energy, contracts, and heats, and the envelope gains energy, expands, and cools.

The contracting core is more important for the ultimate evolution of the star, but what astronomers actually see in their telescopes is the outside of the envelope. The outside, like the whole envelope, gets cooler and hence more red in color. Inside, the helium burns at a high rate and provides a high brightness for the star. At a given surface temperature, astronomers categorize the brightest stars as giants and the rather dim stars as dwarfs. The stars we are describing have become what astronomers call *red giants*. The size of such stars also becomes very large as the envelope expands, so the star is also a giant in terms of its extent, even though this is not technically what an astronomer means by giant. For instance, a blue supergiant is much brighter, but much smaller than a red giant. In any case, red-giant stars swell from the size of the Sun to extend well beyond the radii of the inner planets of the Solar System. We expect the Sun to undergo this transition in about another 5 billion years, at which time the inner planets should be engulfed and evaporated. The Sun will live about 1 billion years, about 10 percent of its total lifetime, as a red giant and then die.

To be fair, this explanation for the formation of a red giant by exchange of energy from the core to the envelope is a little simplistic. The exchange of energy does happen and is one factor, but experts still argue about the best way to understand why red giants form. The computer models show that it happens, but the process is a complex, nonlinear interaction of the star with gravity and is not that susceptible to simple, this-is-the-key-factor-type explanations. In a certain sense, the formation of a red giant involves an instability. It is as if you push a book toward the edge of a table. Nothing much happens for quite a while. If you push too far, however, the book will land on the floor. As the core shrinks in a star that has consumed its central hydrogen, there comes a point where the envelope "falls" outward, coming to a lower energy solution that couples the pressure in the core and envelope with gravity.

Stars with appreciable mass pass through several burning stages after they become red giants. They also spend about 10 percent of their total life in this phase, with each stage progressing faster than the one before. After each successive fuel is exhausted in the center, the star finds itself without a source of heat, so the core contracts until the material that was formed by the previous burning phase becomes hot enough to burn. The core must become hot enough to overcome the charge repulsion among the greater number of protons in ever more complex nuclei. In massive stars, hydrogen burns to become helium in the basic way we described in Chapter 1. The details are different than those for the Sun, but the net outcome is the same: four protons must combine to make a helium nucleus with the creation of two neutrinos.

In stars with the mass of the Sun and in more massive stars, helium burns to become carbon and then oxygen. The reason for this is that the simplest interaction one can imagine, combining two helium nuclei, makes a nucleus with four protons and four neutrons. For reasons that have to do with the details of how the nuclear force works, the nuclear attraction of that combination of protons and neutrons is not able to overcome the charge repulsion of the four protons. The combination of four protons and four neutrons is unstable. A nucleus with four protons and four neutrons falls apart and hence cannot be one of the steps in nuclear burning to produce a heavier "ash" from a given fuel.

Nature finds a way around this bottleneck by utilizing the more rare process by which three helium nuclei occasionally become close enough to combine under the control of the nuclear force. The result is a nucleus with six protons and six neutrons, the element carbon! This is where all the carbon necessary for life arises. As the helium burns in this way, some of the as yet unconsumed helium can combine with the newly formed carbon to make an element with eight protons and eight neutrons, the element oxygen, another critical agent for life as we know it.

In the Sun, thermonuclear burning is expected to halt with the production of carbon and oxygen for reasons that will be addressed in Section 3. For sufficiently massive stars, the process continues. Ultimately, a complex of heavier elements forms. Prominent among these substances are the elements neon, magnesium, silicon, sulfur, argon, calcium, and titanium. That may seem an odd assortment, from a noble gas to the stuff in your bones to a metal used in submarine hulls, but there is a common factor. Each of those successive elements consists of two more protons and two more neutrons than the one before. Stars produce this chain of elements in especially large abundance because each is essentially made up of the basic building blocks of helium nuclei: three for carbon, five for neon, and ten for calcium. Each successive element contains more protons than the last because each phase of burning is one of fusing lighter nuclei into heavier ones. More protons means more charge repulsion to be overcome by higher temperatures. The star obligingly provides the higher temperature in the core by contracting whenever it finds itself without any nuclear energy input to balance the radiation energy lost to space.

This seductive process by which a star prolongs its life actually just puts it deeper and deeper in the grip of gravity. Gravity will ultimately win the battle.

2. Stellar Winds

Before delving into the depths of the stellar cores, let us consider some of the important processes in the outer parts of the star by which some stellar matter can escape the grip of gravity.

On the Earth, a wind is the actual motion of matter, air molecules moving en masse from one place to another. In addition to radiation, the Sun emits a wind of particles, mostly hydrogen, that flows out into space in all directions. For the Sun, the cause is not precisely known. It may be due to the turbulent, boiling surface pumping magnetic energy into the outer layers and expelling them. Evidence for the solar wind is in the tails of comets. Comet tails always point away from the Sun, wafted by the stellar breeze, whether the comet is headed toward or away from the Sun. The solar wind is interesting, but the total amount of matter expected to be lost from the Sun during its lifetime on the main sequence is negligible. The nature of a wind from a star is illustrated schematically in Figure 2.2.

For more massive stars, the story is different because the loss of mass to a wind can substantially alter the evolution of the star. For massive stars, the mechanism to expel matter is thought to be the pressure of the intense radiation that flows from the star. Although we turn to the Sun for warmth, we do not usually think of the pressure of the sunlight on our faces. It is there, but it is very small. In space with no competing effects, the pressure exerted by the photons of radiation streaming out from the Sun can be appreciable. There are dreams to have a sail plane race in space with all the craft powered by the pressure of the solar radiation.

The power emitted in radiation from a star is known as the star's *luminosity*. The luminosity is the amount of radiation energy that flows from a star in a given time. The pressure exerted by the radiation is proportional to the luminosity. As the mass of a star goes up, the luminosity and the pressure exerted by the radiation increase by about the third power. That means that if you consider a star of twice the mass, the luminosity goes up by a factor of eight. For a sufficiently large stellar mass, the large radiation pressure associated with the large luminosity becomes a dominant process. In massive, bright stars, the pressure of the radiation flow is much greater than it is for the Sun. For massive stars, the radiation pressure in the outer parts of the star can be so great that matter is actually blown off the surface of the star in appreciable quantities. This is thought to be the mechanism behind the large stellar winds from massive stars.

Because of the very strong stellar winds, massive stars can lose a large part of their mass while they slowly burn hydrogen on the main sequence. After a massive star leaves the main sequence, the lifetime gets shorter, but the rate of loss of mass in a wind is much higher. The result is that appreciable mass can be lost in the red giant phase even if relatively little has been shed on the main sequence. Large mass loss can affect the evolution of the star. If the wind is strong enough, the entire hydrogen envelope can be expelled, thus exposing the core of helium and heavier elements.

Stars with less than about 30 solar masses can lose enough mass in a wind that they end up with substantially less mass than they had when they were born. This does not affect the qualitative behavior of the star, but it can alter details of the evolution. Stars of this relatively low mass do not have sufficiently strong winds to expose the core. In some cases, however, a binary stellar companion can tug the outer mass off and still produce a bare core with little or no hydrogen blanket. This and other effects of binary companions will be discussed in Chapter 3. Stars with mass between about 30 and 50 solar masses do become red giants but then are thought to undergo such an appreciable loss of mass to a stellar wind that the red giant envelope is ejected anyway, exposing the core. For stars in excess of about 50 solar masses, there is no observed red-giant phase. The interpretation is that so much mass is lost on the main sequence due to a strong stellar wind that no outer hydrogen envelope is left to expand and become a red giant.

If the entire hydrogen envelope is lost to a wind, the bare core composed of helium and heavier elements should be exposed to view. We observe stars of just these properties. The *Wolf-Rayet stars* have little or no hydrogen on their surfaces and are seen to have strong winds themselves. Wolf-Rayet stars are thus thought to be the result of strong mass loss by winds from massive stars. This means that massive stars may not be red giants when they undergo core collapse but rather Wolf-Rayet stars. Whether Wolf-Rayet stars explode as supernovae or collapse to make black holes or some mix of both is not known.

As already noted, radiation pressure exerted by a star is proportional to its luminosity. There is a critical luminosity above which the outward radiation pressure exceeds the inward pull of gravity. In this case, the result is not just a wind but rather a complete disruption of the balance of pressure and gravity in the star. This limit to the luminosity is called the *Eddington limit*, after the early British astrophysicist, Sir Arthur Eddington, who first realized the key role radiation could play in stars. The critical Eddington limit luminosity is proportional to the mass of the gravitating star; it is the gravity of that mass that the radiation pressure must overcome. A star of fifty times the mass of the Sun is so bright that it is near the Eddington limit. That is why it blows such a substantial wind.

In Chapters 5, 8, and 10, we will also talk about circumstances when matter is dropped onto a compact, high-gravity star, like a white dwarf, a neutron star, or a black hole. Radiation pressure can also play a crucial role in these circumstances. If matter falls onto a star of high gravity, a great deal of heat and luminosity are generated. The resulting luminosity can exceed the Eddington limit, and the associated radiation pressure can actually prevent matter from falling onto the star at any higher rate. If the rate were higher, the excess matter would be blown away rather than falling on the star. The rate of infall of mass that just provides the Eddington luminosity is known as the *Eddington mass accretion rate*. In principle, a balance can be achieved in which the radiation pressure allows only enough mass to fall onto a compact star to generate the Eddington limit luminosity that provides the pressure. A star in such a balance will automatically radiate precisely the Eddington limit luminosity and the mass infall onto it will be precisely the Eddington mass accretion rate.

3. Quantum Deregulation

Let us now return to what happens in the guts of a star as it evolves. Section 1 described thermonuclear burning in conditions where the thermal pressure dominated over the quantum pressure. In this situation, the star can regulate its burning because the star will heat up when it loses energy and cool off if it gains energy. The process of contracting and heating and passing from burning phase to burning phase is halted if the core of the star gets too dense. At high density, the electrons are squeezed together so much that the exclusion and uncertainty principles comes into play as described in Chapter 1. In this circumstance, the quantum pressure of the electrons exceeds the thermal pressure of the electrons and atomic nuclei. This happens first for lower-mass stars that are denser than high-mass stars at a given burning phase.

In this compact state governed by the quantum pressure, the star loses the ability to heat and ignite a new, heavier nuclear fuel. Any nuclear fuel that does burn under these conditions is not regulated. The star loses the ability to control its burning and its temperature. The quantum pressure deregulates the temperature; the thermostat of the star is broken.

The reason for this quantum deregulation is that the quantum pressure does not depend on temperature. If the star supported by the quantum pressure loses a net amount of energy because the nuclear fires have gone out, the pressure remains unchanged. There is no contraction to provide heat, so the temperature just drops as the heat is lost. A star, or portion of a star supported by the quantum pressure, behaves as you would think normal matter should: when it radiates away heat, it cools off, as illustrated in Figure 1.3. If a nuclear fuel ignites in a star supported by quantum pressure, the burning adds some heat. The pressure does not rise, so there is no expansion to absorb the heat. The temperature simply rises. The nuclear burning is very sensitive to the temperature, however. Thus at the new higher temperature, the burning proceeds even faster, raising the temperature even more. The nuclear rates can become so fast that the energy they produce can blow the star to smithereens. A star supported by the quantum pressure has an unstable, unregulated temperature. The temperature will decline toward absolute zero if there is no nuclear burning. The temperature will rise sharply if there is nuclear burning. The star has a broken thermostat. Even more, it is as if, when your house gets a little hot, you set the rafters on fire. The way in which the quantum deregulation sets stellar rafters aflame is given in Chapter 6.

Most stars reach this state of unregulated temperature and burning after helium has burned out in the core. The core is then composed of a mixture of carbon and oxygen. The core typically has a mass about 60 percent of the mass of the Sun, independent of the total mass of the star. This applies to all stars with mass up to about ten times the mass of the Sun, and that is most of the stars. The remaining mass is in the extended red-giant envelope. While the envelope is as big as the Earth's orbit, the core is very tiny by the time the quantum pressure becomes dominant – a few thousand kilometers in diameter, about the size of the Earth. The resultant density can be a million to a billion grams per cubic centimeter. Ordinary earthly matter, or that in normal stars, is about one gram per cubic centimeter. To get such high densities that the quantum pressure comes into play, a whole building, such as the seventeen-floor physics building in which I work, would have to be packed into the volume of a sugar cube. Only gigantic gravitational forces can achieve such a compaction.

This small dense core is immediately surrounded by two narrow, very bright shells of matter where helium and hydrogen are burning. These shells are the last remnants of the stages of hydrogen and helium burning in the center of the core through which the star has already passed. The pressure of radiation from these burning shells causes the envelope to pulsate violently and blow matter from the star. The outer envelope is ejected in this process.

Astronomers see the outcome of this process as a shell of gas proceeding outward from the star. These expanding, ejected shells are called *planetary nebulae*. They have nothing to do with planets except that they are often sufficiently extended in photographs that, like planets, they do not have a "starlike" point image. Planetary nebulae were misnamed by early astronomers, but the name has stuck.

When the envelope is ejected, the core of the star is left behind. Supported by the quantum pressure of its squeezed electrons, the core cools off to become what is known as a *white dwarf*. When a white dwarf forms, it still has a great deal of heat and looks blue-white to an astronomer. The term "dwarf" comes from the low luminosity. The white dwarf has such a small surface area that the white dwarf is dim despite its high temperature. White dwarfs are also tiny in size and hence dwarflike in that sense, even though, again, that is not the meaning astronomers have attached to the word. We will return to white dwarfs in Chapter 5.

4. Core Collapse

Massive stars continue to evolve, forming cores within cores of ever heavier elements until the innermost regions are turned into iron. Iron is a very special element in the Universe. It is almost composed of fourteen helium nuclei but is a little more complex because two of the protons have converted to neutrons, so iron has four more neutrons than protons. By the happenstance of the nature of the strong nuclear force among protons and neutrons, the fifty-six particles of an iron nucleus are more tightly bound together than in any other element (with the possible exception of a couple of exotic elements like rare isotopes of nickel, which cannot easily be formed in nature). Iron happens to be at the bottom of a nuclear "valley" toward which all other elements would like to fall, just as rocks roll down a mountainside, as shown in Figure 2.3. The difference is that the force causing the settling toward the "bottom" is the nuclear force, not gravity. All elements lighter than iron would energetically prefer to merge together to form iron. They are prevented from doing so only by the repulsion of the electric charge on the protons. Stars are nature's way of overcoming the electrical repulsion and rolling the elements down the nuclear hillside to the bottom where iron comfortably sits.

As rocks roll downhill, they turn their gravitational energy into other forms, such as noise, breaking trees, dislodging other rocks, and compacting and heating the soil where they land. This complex process conserves the total energy. When the rock is at the bottom of the valley, it can roll no farther, and no more energy can be obtained from it. A similar process occurs in forming iron. Energy is released as light elements fuse together to form heavier ones closer to iron. Elements heavier than iron are on the other side of the valley from the light elements, but their protons and neutrons are also less tightly bound than those of iron. These elements approach iron by splitting apart into lighter elements in the process called *nuclear fission*. This process is the one that powers nuclear reactors, but it does not occur naturally in stars to any great extent because the stars are composed of elements lighter than iron.

Energy cannot be obtained from a rock at the bottom of a valley. On the contrary, to move the rock, energy must be invested to lift or roll the rock back up the hillside from which it originally fell. What about a stellar core made of iron? No more nuclear energy can be derived from that core. With no nuclear energy input, the star radiates a net amount of energy into space. The massive stars that develop iron cores are typically hot enough that thermal, not quantum, pressure dominates their structure. Thus when such stars lose energy, gravity squeezes them, and they heat up. Gravity naturally makes energy available to the iron. The response of the iron is to roll up the nuclear hillside. Most of it breaks apart into the lighter nuclei from which it originally formed. Some of the iron will undergo fusion reactions that lead to the heavier particles on the other side of the valley. Both of these processes require energy. Rather than firing up a new nuclear reaction to repel the squeeze of gravity, the iron absorbs heat energy from the star. The hot particles exerted the thermal pressure to support the star. When the particles lose energy to the breakup of iron, the pressure cannot rise. Gravity then compresses the iron core even more, but the iron continues to break apart, absorbing the energy and preventing a rise in pressure to withstand the stronger gravity.

The result is another example of energy conservation, with iron playing the negative role of a sponge rather than a source of energy. With iron absorbing energy, gravity overwhelms the weakened pressure. The formation of an iron core in a massive star signals the end of the thermonuclear life of the star. At that point, the star is doomed. Gravity prepares to deal the death blow. The core collapses in a mighty implosion!

5. Transfiguration

As the iron disintegrates into lighter elements in the collapse, the core plunges to a smaller size, and the density skyrockets. The rising quantum pressure of the electrons is too feeble. The electrons stop fighting the gravity and disappear. They do this by combining with a convenient proton (a mutual suicide pact determined by the conservation of charge) and forming a neutron. To conserve lepton number, a neutrino must be produced for every electron that disappears, as discussed in Chapter 1. The result is that in the collapse of the iron core, the electrons and protons disappear to be replaced by neutrons and a flood of neutrinos. The result is the formation of an entirely new type of astronomical object, a *neutron star*.

A neutron star is composed almost entirely of neutrons. The mass of a typical neutron star is somewhat more than that of the Sun, and its radius is about 10 kilometers. This is only about the size of a small city like Austin. The density at the center of a neutron star exceeds that in the nucleus of an atom. In a sense, a neutron star is a gigantic atomic nucleus held together by gravity. A typical density would be about 10^{14} grams per cubic centimeter. To attain such a density, an entire city like Austin would have to be packed into the size of a sugar cube.

The gravity of a neutron star is fantastically large and must be balanced by an equally large pressure. At a large enough density, the quantum pressure of the neutrons can become sufficiently great to overcome the force of gravity and restore the condition of dynamic equilibrium. The quantum pressure of the neutrons is aided by the nuclear force. As described in Section 1, the nuclear force has no effect on particles that are a large distance apart; however, when they get quite near, the nuclear force pulls them together. The nuclear force is “attractive,” like gravity or opposite charges. An important detail mentioned in Chapter 1 comes into play when nuclear particles are packed very close together. At very small distances between particles, the nuclear force drives baryons apart. The nuclear force becomes “repulsive,” like similar charges. This repulsive force on closely packed neutrons helps to hold them apart and contributes to the pressure that supports a neutron star. As for white dwarfs, there is a maximum mass to neutron stars, a maximum mass that can be supported by the combined quantum and nuclear pressure of neutrons. The quantum effects are known precisely, but the nuclear force is not exactly established, so this pressure, and hence the total mass it can support, are still somewhat uncertain. The best guesses based on sophisticated calculations of nuclear matter are that the maximum mass for a neutron star is of order 1.5–2 solar masses.

The process of collapse and renewed support by the quantum pressure of the neutrons and the repulsive nuclear force among very compact neutrons is quite rapid. It requires only about a second in a star that has lived for millions and millions of years in tranquillity. The details of this process will be explored in Chapters 6 and 7. A summary of what we have learned about neutron stars will be given in Chapter 8.

There is no guarantee that the process of core collapse will result in the formation of a neutron star. A tremendous amount of gravitational energy is released in the collapse, a hundred times more energy than is necessary to blow the outer layers away from the star. One reason that the nature of neutrinos was stressed in Chapter 1 is that they play a dominant role in core collapse. The majority of gravitational energy produced in the creation of a neutron star, more than 99 percent, is given to the neutrinos. The neutrinos escape from the collapsing iron core and the newly formed neutron star and carry most of the energy off into space.

The degree to which the remaining energy available from collapse may be directed outward rather than inward is not clear. If a fraction of the energy is used to blow off the layers of the star surrounding the original iron core, then a neutron star can be left behind. On the other hand, if insufficient energy is directed outward to eject the outer portions of the star, then the outer layers rain inward. A neutron star may form momentarily from the collapsed iron core, but then the rest of the star falls inward. Because we are talking about a process that occurs in massive stars, the mass that falls in will far exceed the maximum mass a neutron star can support. The neutron star will rapidly be crushed out of existence in a process of total, ultimate collapse. The result will be the unique gravitational entity that astrophysicists call a *black hole*. A black hole is an object for which all the mass has been crushed to what is effectively zero volume. All that remains is the gravitational field that becomes overwhelming at distances close to the center of the collapse. We will study the details of these fantastic objects in Chapters 9 and 10.