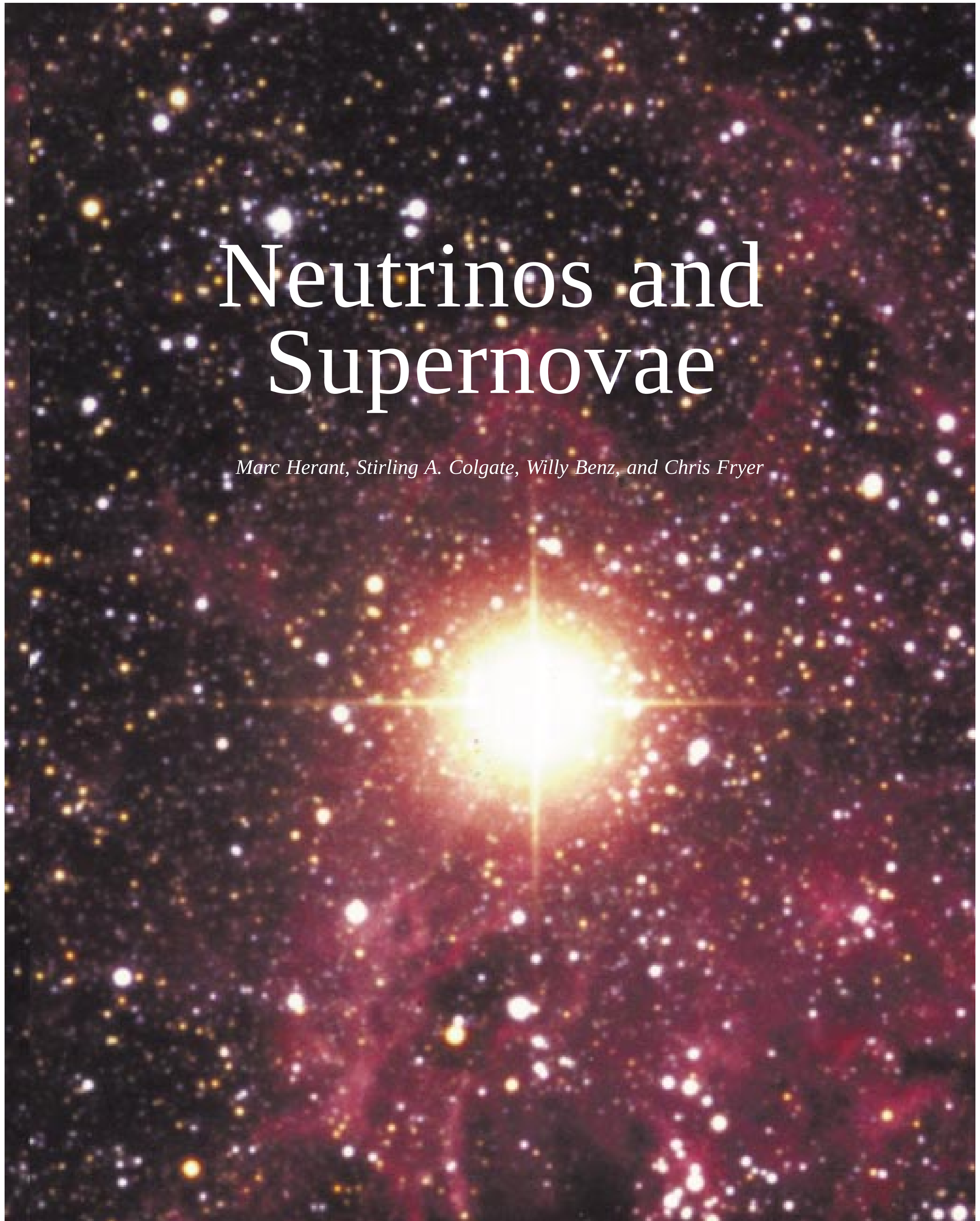


Neutrinos and Supernovae

Marc Herant, Stirling A. Colgate, Willy Benz, and Chris Fryer

Evanescent, fleeting, transient—these words come to mind when describing the elusive neutrino. Although neutrinos clearly play a key role in nuclear physics through the weak force, their interactions with matter are just that—weak. Under typical conditions, a neutrino is 100 billion billion (10^{20}) times less likely than light to interact with matter, and a neutrino will pass straight through our planet Earth as effortlessly as the breeze through an open window. Is it any wonder that the direct physical manifestations of the neutrino always seem so tenuous?

But there is one exception to the neutrino's demure role. It occurs in the heart of massive stars, deep within the stellar core. When a massive star dies, it does not go peacefully. Instead, it makes a spectacular exit—the most powerful explosion known to occur in the universe. Astrophysicists call this exploding star a supernova, and in an ironic reversal of roles, it is the quiet neutrino that is chiefly responsible for the cataclysm.[1]

Over the years, scores of researchers (including quite a few from Los Alamos who have a particular interest in large explosions) have constructed an in-depth theory explaining how and why massive stars explode. Stars emit light and shine because they "burn" nuclear fuel. But the amount of nuclear fuel is limited.

When a star exhausts its fuel supply, something startling happens: the forces that support the star's core quickly retreat, and the core is almost instantly crushed by gravity. The compression is so severe that, in less than 1 second, the core reaches virtually unparalleled conditions of temperature and density. Theoretical physics predicts that, under these unique circumstances, vast quantities of neutrinos are produced that carry off the enormous amount of energy released by the collapse of the core. A few of those neutrinos are absorbed by material that is plummeting toward the compacted core. The falling matter becomes very hot, expands, and surges outward. Eventually, the star erupts in a furious explosion that ejects the star's outer layers into space. All that remains of the once enormous star is its center, now transformed into a tiny, incredibly dense object called a neutron star.

Figure 1. The Crab Nebula
Located about 6,500 light years from Earth, the crab nebula is an expanding gaseous cloud that was hurled into space when a giant star exploded. That supernova was visible day and night for several weeks in July 1054. Even today, the visible emission from the nebula is still greater than 75,000 suns. At the center of this brilliantly glowing cloud lies a spinning neutron star, which is the core of the original star.
© Malin/Pasachoff/Caltech, color photograph by David Malin.

This pivotal and wondrous function of the neutrino, so much in contrast with its usual marginal position, received triumphant vindication in February 1987, when two underground detectors recorded a burst of neutrinos and a spectacular supernova was later observed by astronomers worldwide. The astrophysical community was elated! For the first time, the theoretical relationship between neutrinos and supernovae was empirically confirmed.

That confirmation was a climactic moment in a long history of supernovae observations. For centuries, mankind has been fascinated by the sudden, yet brief, appearance in the sky of a superbright star at a spot where there was none before. Chinese astronomers recorded one such event as early as 185 A.D. But such sightings are rare, as supernovae are infrequent events. They occur on average only once every 50 years or so within a given galaxy. The inhabitants of the northern hemisphere have not been treated with a supernova visible to the naked eye since 1604.

But it is also true that there are billions of distant galaxies within the universe, and supernovae tend to be highly conspicuous. So much energy is released during the explosion that, for a short time, the star may outshine an entire galaxy containing over ten billion stars. In the last hundred years, astronomers have monitored more than a thousand supernovae. They have been able to examine in great detail the expanding nebulae that linger for centuries as remnants of the explosions (Figure 1).

Indeed, astrophysicists have been able to study even the exotic neutron stars that form under the remarkable conditions found inside supernovae. Neutron stars are made up almost ßentirely of neutrons. Only 20 kilometers or so in diameter but more massive than the Sun, these singular objects are so dense that a basketball-sized chunk would weigh about 10 trillion tons. Their possible existence was predicted

[1]Supernovae are classified as Type I or II. Type I supernovae have no hydrogen in their emission spectra and are generated (usually) by old stars of small mass. In this article, we will only describe the more common, Type II supernovae.

y J. Robert Oppenheimer and George Volkoff in the late 1930s, and hen Fritz Zwicky suggested that eutron stars might be created in upernova explosions.

Neutron stars remained but a theo-etical conjecture until Jocelyn Bell and thers discovered pulsars in 1967. ulsars are often found at the center f supernova nebulae. They emit xtremely regular, very intense pulses f radio waves. Only a spinning star with a diameter comparable to the readth of a small city could lead o such an extraordinary extraterrestrial ignal, and pulsars were quickly dentified with neutron stars.

In this article, we outline much of what has been learned about Type II upernovae and describe in detail how ld stars of more than 8 solar masses re thought to die. (A star's mass is lways stated relative to the Sun's mass, which is 2×10^{33} grams and is enoted by the symbol $M_\odot$. Therefore, solar masses is written as $8M_\odot$.) However, before we discuss the death f stars, we will digress and first iscuss how those stars live.

A Star's Life

A star performs one of nature's finest high-wire acts. It carefully and ontinuously maintains its balance gainst the omnipresent pull of gravity. is gravity that initially shapes a primordial cloud of gas[2] into a spherical tar, and it is gravity that collapses and ompresses the gas. Compression, how-ver, increases both the temperature nd the internal pressure of the gas. Once that pressure is sufficient to coun-eract gravity's pull, the star stops hrinking. If for some reason the inter-al pressure temporarily exceeds the ravitational force, the star will expand. The pressure will then drop, and the expansion will stop once the pressure is again equal to gravity. As long as the internal pressure can be sustained, a star will neither expand nor contract, but it will maintain a state of *hydrostatic* equilibrium, wherein gravity and the internal pressure are balanced.

But a star is also hot, with a core temperature of millions of kelvins. Heat and energy flow out from the core and through the mantle to be emitted as light from the star's surface. The star shines brilliantly. Yet for all its serene beauty, starlight is a relentless drain on the star because energy is irretrievably lost to the cold vacuum of space. If energy were not continually regenerated, the loss would cool the gas and sap the internal pressure, causing the star to slowly contract.

New energy comes from thermonu-clear fusion, the process whereby two light, atomic nuclei merge to form a single, heavier nucleus. Because fusion releases a significant amount of energy, the star can counteract radiative losses simply by sustaining a sufficient fusion rate. A star achieves and maintains a *thermal* equilibrium in addition to its hydrostatic equipoise. A star's life consists of balancing the opposing forces of gravity and pressure, while simultaneously matching all energy losses with the gains produced by thermonuclear fusion.

Evidently, this state of total equilibrium cannot be maintained. The amount of nuclear fuel available to the star is finite, and as lighter elements burn, fuel slowly disappears. Initially, it is only the primordial hydrogen that burns. The burning takes place in the core, which is the hottest and densest part of the star. (See the article "Exorcising Ghosts" on page 136 for a description of the energy-producing reactions in the Sun.) In part because hydrogen burning releases a lot of energy, only a modest rate of fusion is needed to stabilize the star, and the hydrogen reserves last a long time. A star will burn hydrogen for millions to trillions of years.[3]

At some point, however, all the hydrogen in the core will have fused into helium. Because helium burning requires much higher core temperatures and densities than exist at this stage of the star's life, fusion temporarily stops. Without an energy source, the core begins to cool, the core pressure begins to drop, and gravity again compresses the star. As before, the gravitational compression does work on the stellar gas so that, somewhat counterintuitively, the loss of fusion energy leads to a *rise* in the core temperature. Once the tem-perature and density are sufficient to fuse helium into carbon, new energy is released, and equilibrium is quickly restored. The star still consists almost entirely of hydrogen gas, but the hydrogen now surrounds a helium gas core that is undergoing fusion.

Eventually, the helium fuel is depleted. Fusion stops, and the star cools and contracts until it is again able to initiate the burning of a new fuel. This is a repetitive process, so that the aging star will burn in succession carbon, neon, oxygen, and finally silicon. Because of the various burning stages, the star develops a layered structure consisting of many different elements, as seen in Figure 2.

However, as the elements get heav-ier, the amount of energy released per reaction decreases. As a result, the burning rate must increase in order to liberate enough energy to sustain the internal core pressure. In addition, neutrinos are produced much more readily within the core during the late burning stages of stellar evolution. Because the neutrinos remove even more energy from the core, they are yet another factor that leads to an increased burning rate. (See the box "The Urca Process" on page 168.)

The primordial gas consists of hydrogen, ome helium, and trace amounts of other light lements. This gas formed in the first few minutes after the Big Bang. See the article Dark Matter and Massive Neutrinos" on age 180 for more details.

[3]The time it takes for a star to burn its fuel decreases rapidly as a star's mass increases. Compared with their lighter cousins, massive stars are squeezed harder by gravity and therefore require significantly more pressure to remain stable. They burn their fuel considerably faster. Whereas the Sun will live approximately 20 billion years, a 15 $M_\odot$ star will only live about 20 million years.

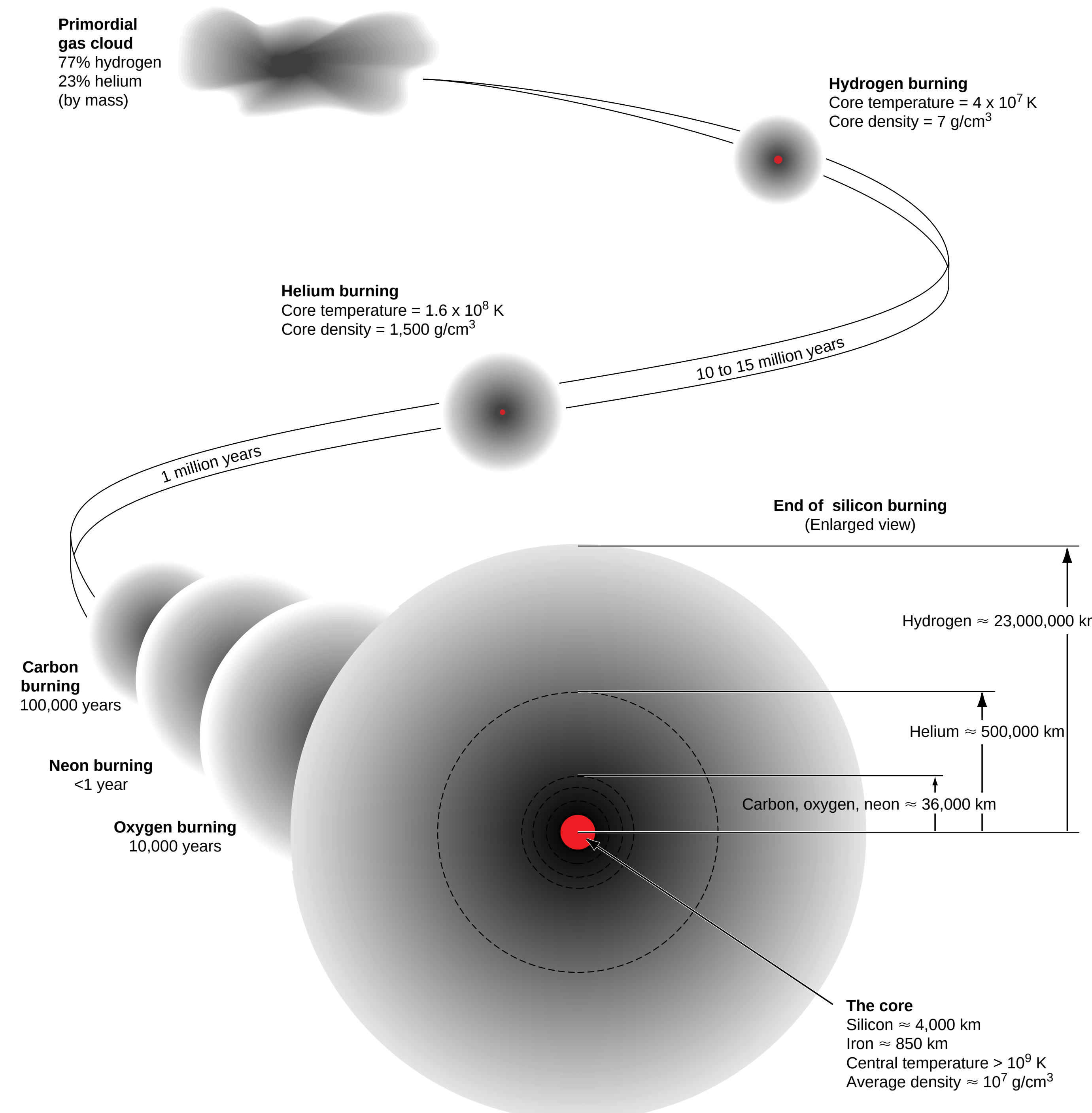


Figure 2. The Life of a Massive Star

A star is born when a huge cloud of primordial gas is compressed by gravity. The compression raises the density and temperature of the gas to the point that hydrogen nuclei can fuse into helium within the star's core. Both hydrostatic and thermal equilibria are quickly established (see text). The star will burn hydrogen for tens of millions of years, gradually accumulating helium in its core. Eventually, the core is fully depleted of hydrogen, and fusion stops. The core cools and contracts, which leads to higher pressures and densities, and a new burning phase begins. Helium is fused into carbon within a hotter, denser, and much smaller core, even though the star itself has become larger during this phase. Over the course of its lifetime, the star's core will become smaller and much denser as it burns in succession carbon, neon, oxygen, and silicon. At the end of silicon burning, the star has developed a layered structure, shown above for an 18$M_\odot$ star. Note the tiny silicon and iron core. The core is 100 million times more dense than the hydrogen layer.

The Urca Process

During the late burning stages, core electrons become energetic enough to react with protons inside heavy nuclei through the weak interaction. The proton turns into a neutron while the electron (e^-) turns into an electron neutrino (ν_e). The neutrino escapes from the core and removes energy. The newly formed nucleus then undergoes beta decay. As a result, the nucleus is restored to its original state, and an electron–electron antineutrino ($\bar{\nu}_e$) pair is created. The $\bar{\nu}_e$ similarly escapes the core. The nucleus can now endlessly repeat this sequence whereby escaping neutrinos drain the core of energy. For a nucleus containing N neutrons and Z protons, written as (N, Z), the two-step process is represented by the following reactions:

$$(N, Z) + e^- \rightarrow (N+1, Z-1) + \nu_e \quad \text{(nuclear electron capture) , and}$$
$$(N+1, Z-1) \rightarrow (N, Z) + e^- + \bar{\nu}_e \quad \text{(nuclear beta decay) .}$$

During a conference in Urca, Brazil, physicists George Gamow and Mario Schoenberg noted that the local casino appeared to drain money from gamblers much in the way these reactions drained energy from a star. The two physicists promptly dubbed this set of reactions the Urca process.

Although a heavy star will burn hydro- en and helium for many millions of ears, it will burn carbon for about 00,000 years and oxygen for only 0,000 years. Incredibly, silicon urning lasts but one day.

Silicon fuses to become iron, but nce iron is created, the process of lib- rating energy through thermonuclear usion comes to an abrupt end. Iron is he most stable of all nuclei. Any usion or fission reactions in which iron articipates absorb rather than release nergy. Thus, formation of the iron ore marks the beginning of the end for massive stars. As energy continues to eak out, the core pressure drops, and he core rapidly loses its internal upport. The core physically implodes s gravity causes the planet-sized center o collapse under its own weight. As discussed in the next section, the ebacle is over in less than one second r, literally, within the blink of an eye.

The Core Collapse

Just prior to its collapse, the silicon nd iron core has a radius of about ,000 kilometers and a mass of about $1.4M_\odot$. Once silicon burning ends, the core begins to contract. But two events will quickly turn the contraction into a nearly free-fall collapse.

First, compression causes the temperature in the central region of the core to rise above 5 billion kelvins, or 0.5 million electron volts (MeV) of energy per particle. At that temperature, scores of photons generated within the central core are energetic enough to dissociate iron into helium nuclei and neutrons. It was the fusion of those same light nuclei that allowed the star to continually emit energy during the eons of its life. The energy of gravity now undoes that work, as nuclear absorption of a photon breaks the iron apart and sucks thermal energy from the central core.

Second, because the core density has also been steadily rising, the core electrons condense into a special quantum state known as the degenerate electron gas. (See the box "An Exotic State" on the facing page.) Above approximately 10^{10} grams per cubic centimeter (g/cm^3), some of the electrons (e^-) in that unusual state acquire the 2.25 MeV of energy needed to transform free, unbound protons (p) into neutrons (n):

$$p + e^- \rightarrow n + \nu_e \ .$$

This weak interaction process, called *electron capture*, produces an electron neutrino ν_e that escapes and removes energy. (Note the similarity between this reaction and the nuclear electron-capture reaction discussed in the box "The Urca Process"on this page.)

The probability for electron capture to occur depends on the square of the electron energy. In turn, electrons become more energetic as the core contracts. Higher densities also make encounters between free protons and electrons more and more likely. Thus, as the collapse continues, the rate of the reaction begins to increase dramatically. Free protons and an equal number of electrons disappear as neutrons are produced. The core becomes partially "neutronized." Energy-sapping neutrinos are produced in copious numbers. Despite a rising density and temperature, the rate of cooling inside the central core increases in a runaway fashion as the core implodes.

Along with an increasing cooling rate, the core experiences an ever increasing gravitational force. The strength of gravity varies as $1/r^2$, where r is the radius. As the core shrinks, the gravitational force crushing the core simply gets stronger. The core collapses faster and faster and faster!

Indeed, the collapse would continue indefinitely and create a black hole, if another special quantum state—the degenerate nucleon gas—did not form. A nucleon is either a proton or a neutron. At high densities, the nucleons in the degenerate gas exert substantial pressure and resist being squeezed together. Furthermore, once the central core density surpasses about 10^{14} g/cm^3, nucleons are squeezed so close to one another that very short range, repulsive, nuclear forces come into play. They provide pressure support in addition to that coming from the nucleon degeneracy. The total internal pressure inside the core starts to increase dramatically, and once the

An Exotic State

The incredibly high densities achieved in the stellar core create an exotic form of matter called a degenerate Fermi gas, in which the laws of quantum mechanics hold sway on a macroscopic scale. This gas forms from a set of identical fermions—particles with half-integer intrinsic spin values, such as electrons, protons, neutrons, or neutrinos. The particles in the gas obey the famous Pauli exclusion principle, which states that identical fermions must at all times occupy their own, unique quantum state.* Because states are defined by discrete momentum values, the exclusion principle demands that every particle have a unique momentum and hence a distinct energy.

In an ordinary, classical gas, particles occupy energy states that are distributed about the mean thermal energy of the gas. Typically, most of the low-energy states are unoccupied. But when fermions are forced into such close contact that the exclusion principle applies, a degenerate Fermi gas can form. In that case, particles occupy the lowest possible energy levels and fill states sequentially. This means that the particles are essentially "locked" in their states. They cannot move to lower levels because all lower states are filled. Thus, individual particles cannot lower their energy. Whereas an ordinary gas dissipates energy when particles scatter or radiate photons, the degenerate gas only loses energy by way of particle loss.

A degenerate gas therefore contains a "degeneracy" energy that is largely independent of the thermal energy. But the degeneracy energy grows rapidly with density because each new particle is forced to occupy an unfilled state, and those states always have higher energies. In the superdense core, the degeneracy energy of the gas is enormous—much higher than the thermal energy. Because these arguments also apply to momentum states, and the momentum of particles in a gas relates to the pressure, a degenerate gas exerts a substantial degeneracy pressure that similarly grows with density in a temperature-independent way.

In the core, the electrons begin to form a degenerate gas during the late burning stages. This process boosts the electron energies well above thermal energies and gives them the 0.25 MeV that is needed to drive the Urca process. After the core begins to collapse and the density increases, degeneracy pushes electron energies above the 2.25 MeV threshold of the electron capture process. Finally, it is the growing pressure from the degenerate nucleon gas, formed above 10^{14} g/cm^3, that ultimately halts the collapse of the core.

*Because there are two spin states (up or down), two particles can occupy each state. The basic discussion does not change.

central density surpasses about 3×10^{14} g/cm^3, the pressure becomes so great that the very center of the collapsing iron core—a 10-kilometer-radius "inner core" of unimaginably high temperature and density—effectively becomes incompressible. Its collapse abruptly halts.

Something remarkable then occurs. Much like an overcompressed rubber ball that is suddenly allowed to return to equilibrium, the inner core violently reexpands. A layer of dense matter surges outward at roughly 10,000 kilometers per second, and a strong shock front begins to plow through material that is still falling inward at roughly 60,000 kilometers per second. This dynamic event is often referred to as the *core bounce.*

As explained in the section "Making Stars Explode" on page 171, the shock front quickly loses energy, and the rapid expansion stops. But gravity cannot cause the dense layer of material behind the shock front to recollapse. The pressure of the degenerate electron gas is very strong and can support that matter out to large radii. (Neutrinos also help provide pressure support. That atypical neutrino behavior will also be discussed in detail later.) Thus, a relatively static layer of hot, dense matter—less dense than the inner core but much more dense than the material that continues to fall—forms as a result of the core bounce. This layer grows larger as new infall adds to it. The shock front, which demarcates this high-density layer from the low-density infall, begins to slowly move out. These events are summarized in Figure 3.

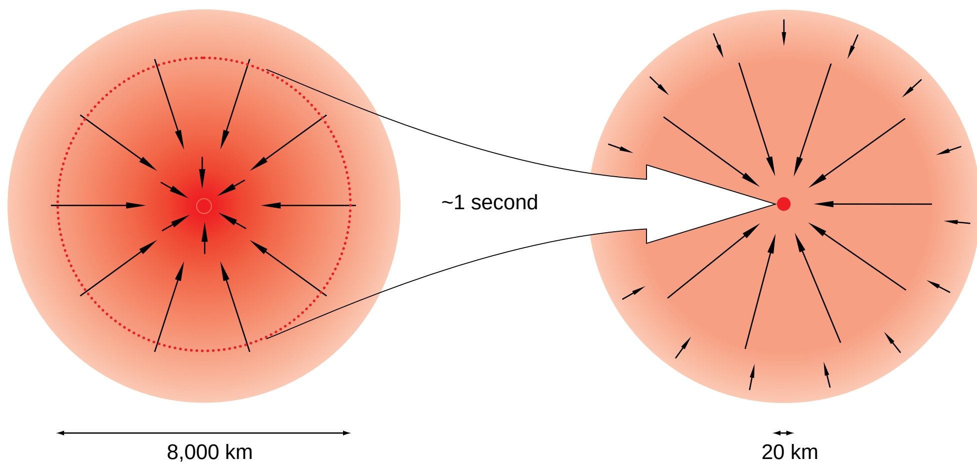
The central portion of that dense layer, out to a radius of approximately 40 kilometers and including the inner core, plays a critical role in the formation of supernovae. That region is called the proto-neutron star (refer again to Figure 3). The proto-neutron star is about $1.2M_\odot$ of electrons, neutrinos, and nuclear matter. After about 10 seconds, it will cool and condense to become the much denser neutron star that is the endpoint of a massive star's evolution. But the supernova explosion is initiated well before the neutron star forms. Thus, the focus of supernova physics is on the development of the proto-neutron star and on the processes that occur in the quasi-static layer of matter that develops behind the slowly expanding shock front.

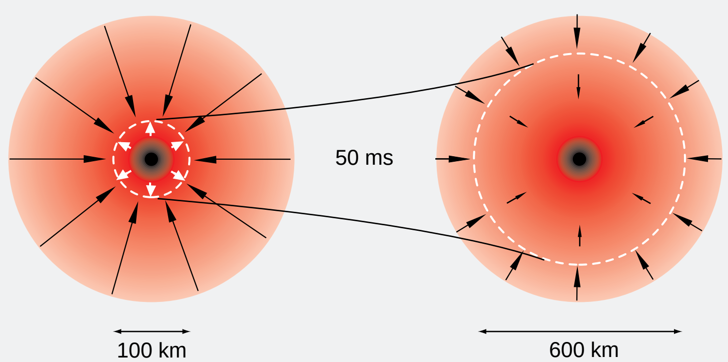
Before we move on, let's take a minute to savor one of nature's most sublime moments. Prior to its collapse, the stellar core is more than twice as large as the moon (although it is about 50 million times heavier!). *In less than one second*, nearly one-third of that mass is compacted into a sphere that would easily fit inside the city of St. Louis, Missouri. The collapse happens so quickly that the remainder of the original iron core, which still extends out to a radius of a few thousand

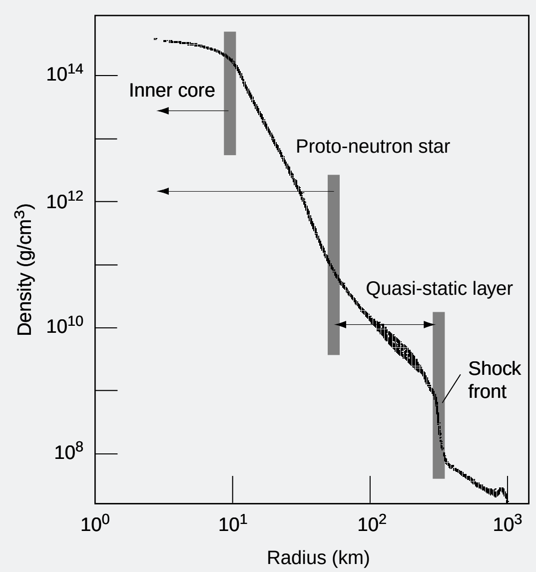
igure 3. Core Collapse, Bounce, and the Postbounce Structure of the New Core

nce silicon burning ends, the star's core rapidly cools and loses pressure. As shown in (a), the entire 8,000-kilometer core undergoes a nearly free-fall collapse and, in less than 1 second, about one-third of the mass is crushed into a sphere approximately 0 kilometers in diameter. The new core, shown in (b) and (c), is vastly denser than the original. In these illustrations, arrows epresent moving matter, and the length of the arrow is generally indicative of velocity.

) Core collapse. Core material nclosed by red dotted line) races ward (long arrows), slowing down nly when it runs into the dense atter in the center. The collapse hapens so quickly that most of the materl outside the core is unaware that e collapse has even occurred. The iginal core had an average density of bout 10^7 g/cm^3, but the average density of the new core (red dot) exceeds 0^{14} g/cm^3, which is more than 0 million times greater than before.







(b) Core bounce. Once the central density of the new core reaches 3×10^{14} g/cm^3, the "inner" core effectively becomes incompressible and no longer collapses. Immediately, the inner core expands and surges outward (white arrows). It quickly swells to a diameter of about 80 kilometers (the proto-neutron star, shown in gray) as a high-velocity shock front (white, dashed line), pushes its way against the infall. Within a few milliseconds, however, the shock loses energy, stalls, and stops its rapid outward movement.

(c) Postbounce structure and density profile of the core. As infall passes through the shock front, the material slows down, and its density increases dramatically (small, black arrows). A dense layer, called the quasi-static layer, begins to accumulate outside the proto-neutron star. The shock front slowly moves outward. The graph of density versus radius (both plotted on log scales) reveals the extent of the quasi-static layer, the proto-neutron star, and the inner core (the very center of the proto-neutron star) 50 milliseconds after the bounce. These regions are typically defined in terms of density. At roughly 3×10^{14} g/cm^3, the inner core extends to a radius of about 10 kilometers and encloses about $0.5M_\odot$. The proto-neutron star decreases in density to about 10^{11} g/cm^3, encloses about $1.2M_\odot$, and extends to about 40 kilometers. The shock front (evident as a sharp change in density) has by this time advanced to an approximate radius of 300 kilometers.

kilometers, is left trying to catch up. This outer region—an iron shell of comparatively low density and internal pressure—offers little resistance to the inward pull of gravity. It is racing toward the proto-neutron star at the incredible velocity of 60,000 kilometers per second.

Finally, most of the star is completely unaware of what is going on. Information about the collapse of the core can only travel as fast as the speed of sound in gas. In the fraction of a second during which the collapse occurs, information can only reach out to a few thousand kilometers. The stellar envelope may extend tens of millions to hundreds of millions of kilometers into space. Thus, much like a cartoon character suspended in midair, most of the star has yet to learn that the rug has been pulled out from under it.

The physics of events leading up to and immediately following core bounce has been fairly well understood for the last twenty-five years, although the models underwent many revisions and modifications as more processes were considered and the role of neutrinos became clearer. But a consensus regarding the postbounce physics many milliseconds after the bounce, the crux of Type II supernovae dynamics, has been much slower to emerge. In a nutshell, the problem is how to turn an implosion into an explosion.

Making Stars Explode

The first modern model of supernovae was presented in 1960 by Stirling Colgate and Montgomery Johnson. It postulates that the outward-moving shock wave produced by the core bounce is sufficiently energetic to continue moving through the outer core like a sonic boom. The shock eventually expels the stellar envelope in a large explosion. This model later became known as the "prompt" mechanism because it argues that the explosion occurs immediately after the bounce.

But in order to continue propagating, the shock needs to beat back the infall of the rest of the star. The postshock temperature is so high, however, that many of the cooling processes that initially led to the collapse of the core, namely, iron photodisintegration and intense neutrino emission, apply equally well to the shock front. As alluded to in the previous section, the shock stalls for all but the most extreme assumptions about the precollapse structure of the star. The bounce shock is thus unable to deliver an explosion and halt the infall of the stellar envelope. In the prompt model, the shock front retreats, and the massive star collapses to a black hole.

Around the same time that prompt models were being developed, scientists realized that there was far more energy available to power supernova explosions than what was typically measured as the kinetic energy of the debris. Based on observations, the explosive energies of supernovae typically tally to about 10^{51} ergs, or 1 "foe." Hans Bethe coined the acronym for (ten to the) **f**ifty-**o**ne **e**rgs. But the entire mass of the precollapsed core eventually ends up in a neutron star whose radius is only 10 kilometers, or one sixty-millionth of the original core's radius! The work done by gravity in compressing the core represents a total energy on the order of 300 foe, or nearly 300 times more energy than what is typically observed to be released by the explosion.

It was recognized that most of the energy is carried off by neutrinos that are created as the core becomes neutronized through electron capture. Today, it seems natural to expect that a small fraction of that energetic neutrino flux powers supernovae. However, in the early 1960s, the idea that neutrinos might do anything dynamical, let alone power an explosion, seemed preposterous.

It was in this context that in 1965 Stirling Colgate and Richard White put forth the first model invoking heating by neutrinos as the mechanism responsible for supernovae. They used a hydrodynamic code to quantitatively analyze their theory. Theirs was the first attempt to simulate the hydrodynamics of a supernova. It was probably the first hydrodynamic simulation ever done in astrophysics.

According to Colgate and White, a supernova is initiated when an iron core collapses directly to a neutron star. As falling matter collides with this very small, incompressible object, a shock front develops that is hot enough to emit neutrinos. Falling material absorbs the neutrinos, heats up, and expands. A mighty explosion ensues.

But the Colgate and White model was eventually shown not to work.[4] It failed, in part, because of a missing piece of neutrino physics that was neither experimentally confirmed nor appreciated until the mid-70s. That missing piece was the neutrino neutral-current scattering.

Neutral-current scattering was a new type of neutrino interaction, and at the high densities found within the core, it resulted in the efficient scattering of neutrinos from nuclei and unbound nucleons. The neutrinos would no

[4]The Colgate and White model is frequently believed to have failed because of an improper postbounce neutrino emission and absorption algorithm. In fact, the model fails because it neglects the effects of neutrino cooling during core collapse. In the model, a supernova develops when a high-temperature iron core collapses. The high temperature leads to a very rapid rate of electron capture, and the core becomes neutronized very quickly and at relatively low densities. A neutron star forms directly from the collapse. The collision energy of the infall onto the neutron star is high enough to generate a high-temperature accretion shock front, and high-energy neutrinos emitted from that front are readily absorbed in the falling matter. Once neutrino cooling was added to the model, the core temperature and hence the nucleon boiloff rate were reduced relative to what Colgate and White had originally considered. Neutronization proceeded much more slowly because there were fewer free protons. In addition, neutral-current interactions were not known at the time. They had the effect of enhancing the neutrino trapping rate, which further retarded core neutronization. Neutrino trapping also led to a large degenerate lepton pressure that supported matter at a radius some 3 to 5 times greater than the radius of a neutron star. Thus, it was eventually shown that the accretion shock front formed at larger radii, and matter that fell onto this shock front was not nearly energetic enough to produce the high-energy neutrinos needed to drive a supernova.

Neutrinos and Supernovae

Neutrino Trapping

The neutrino is the particle that embodies the weak interactions. Up until 1973, neutrinos had been observed to participate only in charge-changing weak interactions, such as electron capture or the reactions making up the two-step Urca process. Two interacting particles exchange a W^+ or W^- boson, and so exchange one unit of electric charge. Charge-changing reactions occur so infrequently that, even at the high densities reached during core collapse, the neutrinos were thought to simply free-stream out of the core.

But in 1973 the neutral-current interaction, long predicted by theorists to be a necessary consequence of electroweak unification, was experimentally verified. This was a new type of weak interaction in which particles exchange a Z^0 boson. Thus, there is no change in the charge states of the participants. Instead, a neutrino could merely scatter from nucleons or electrons. In 1975, Tubbs and Schramm found neutral-current scattering to be favored under the conditions prevailing during core collapse. The neutrino could simultaneously scatter from all the nucleons in a heavy nucleus in a coherent process that boosted the scattering cross section by more than 1 order of magnitude over charged-current processes. At densities above 10^{11} g/cm^3, neutrinos began to scatter from nuclei so often that they became trapped within the core.

One profound consequence of the trapping is that the neutrino density increases enough to reverse the direction of the electron capture reaction:

$$p + e^- \leftrightarrow n + \nu_e \ .$$

Neutrons are transformed back into protons, thus allowing a proton/neutron equilibrium to be established. Neutron star formation is inhibited, and the proto-neutron star forms instead. A second consequence of the trapping is that the neutrino stays in the core long enough to form a degenerate gas. Together with electrons, the two light particles form a *degenerate lepton gas*. It is the lepton gas that stores most of the energy liberated by the gravitational collapse of the core, and it is also the lepton degeneracy pressure that expands the proto-neutron star and supports the bounce shock front long after core bounce has occurred.* Neutrinos of all flavors will scatter via neutral-current interactions, so that ν_μ and ν_τ neutrinos, produced as the core collapses, are also trapped.

*Note that the degenerate lepton pressure is unable to halt the initial collapse of the core. The response of the relativistic lepton gas to further compression is "mushy," and the pressure does not increase very fast when the gas is compressed. The strength of gravity, however, increases nonlinearly with decreasing radius, and the lepton degeneracy pressure alone is insufficient to overcome the increasing pull of gravity as the collapse proceeds.

onger escape blithely from the super-dense proto-neutron star but would nstead become "trapped" and take everal seconds to escape (see the box Neutrino Trapping" on this page). ndeed, neutrino trapping can be used to define" the proto-neutron star, in that nside the proto-neutron star, neutrinos re trapped. Outside the proto-neutron tar, neutrinos no longer scatter strongly but free-stream through the star.

In many ways, neutrino trapping was remarkable. A neutrino is a particle that ordinarily passes through *half a light-year* of lead without scattering! But for a few seconds in the center of a dying star, neutrinos behave like any other particle. They scatter, are constantly absorbed and reemitted, and significantly, exert degeneracy pressure. It is the neutrino and electron degeneracy pressures (the dominant components of what is called the lepton degeneracy pressure) that support the shock front and prevent gravitational collapse.

However, even with neutrino trapping incorporated into the models, efforts to obtain explosions were frequently thwarted. Stellar fizzles were often the result of a detailed calculation. But a major shift in supernova models occurred in 1982, when James Wilson began running computer simulations that tracked events over very long periods of time. Partly because of computer limitations, researchers had tended to model only the core collapse and the events that occurred a few tens of milliseconds after the bounce. Wilson's simulations ran from the start of core collapse to about half a second after the bounce. In his simulations, apparent fizzles evolved into successful blowouts by what later was called the "delayed" (as opposed to prompt) mechanism.

In both the prompt and delayed models, the bounce shock moves out a few hundred kilometers beyond the proto-neutron star and stalls. A stagnant shock front would normally be a sign that all outward expansion has stopped, in which case no prompt explosion occurs and the star inevitably recollapses to a black hole.

But the bounce shock does play a crucial role in setting the stage for the success of the delayed mechanism. After the bounce shock stalls, the degenerate lepton pressure prevents material from recollapsing directly onto the proto-neutron star. By tracking the physics for long periods of time, the simulation showed that the shock front is able to withstand the initially large ram pressure of the infall and is still present when that pressure begins to subside. As a result, the quasi-static layer between the stalled shock and the surface of the proto-neutron star persists longer than the neutrino-diffusion time scale. Some of the energetic neutrinos slowly leaking out of the proto-neutron star can be absorbed in the dense material behind the shock front. Material is constantly heated from below, and it can expand and continue to drive the shock front outward (see Figure 4).

Although delayed models could produce explosions, less satisfying was the fact that, all through the 70s and 80s, supernova simulations seemed to be highly sensitive to the smallest details of how the physics was implemented. Whereas one group might obtain explosions, another would get fizzles simply because the approximations used in the modeling were different. This was worrisome not only because it put any calculations at the mercy of a new wrinkle in the theory, but also because real supernovae do not seem to have such problems. Explosions of fairly uniform energies, always of the order of 1 foe, appear to be produced quite readily. Supernova theory seemed trapped by an endless cycle of successful and failed explosions. Sheer desperation led astrophysicists to consider numerous alternative theories involving core rotation, nuclear burning, magnetic fields, and other processes. However, none of these worked well. What astrophysicists really needed was some sort of lucky break, and on February 24, 1987, they got it.

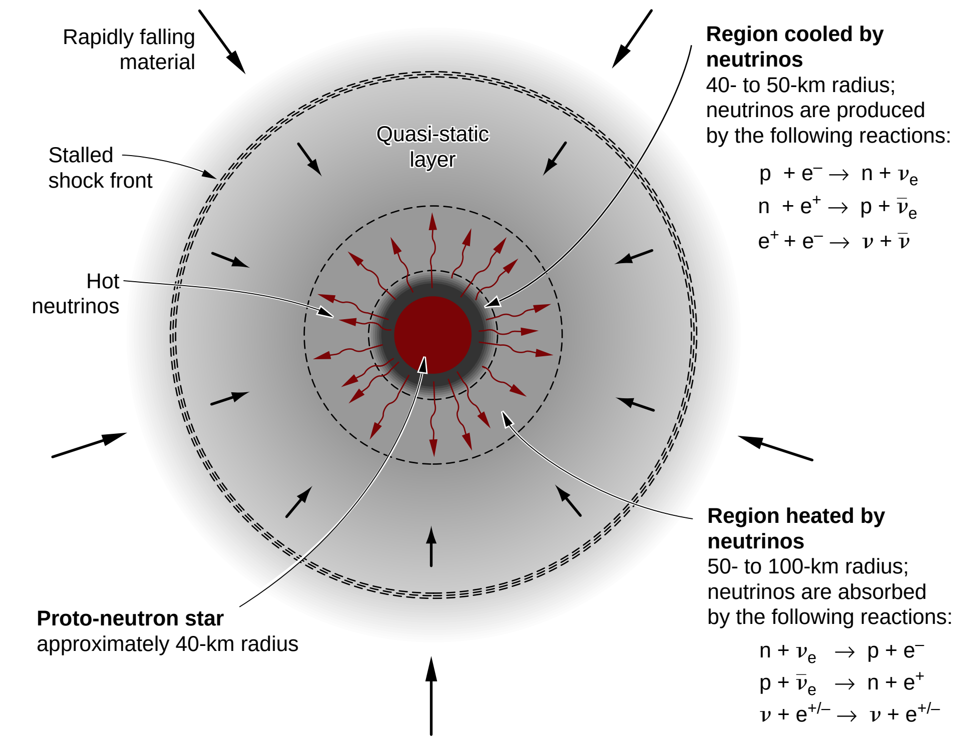


Figure 4. Behind the Front: Heating Matter with Neutrinos
As a result of core bounce, a shock front moves beyond the ultradense surface of the proto-neutron star. The shock loses energy as it propagates and stalls. It is prevented from recollapsing by the pressure support of the degenerate lepton gas, and so it remains at a relatively stable radius, creating a quasi-static layer of dense matter. Some of the energetic neutrinos leaking from the proto-neutron star deposit their energy in the quasi-static layer. The matter expands and becomes buoyant. The neutrinos, therefore, transfer energy out of the extremely high temperature core and into a large mass of lower-temperature material.

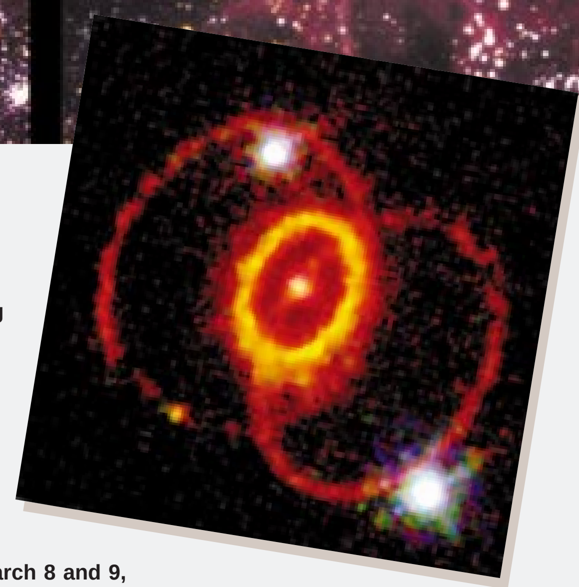
Supernova 1987A

Supernova 1987A (SN1987A), the first supernova seen in 1987, owes its major impact on supernova theory to one reason: it occurred relatively nearby. It flared up a modest 170,000 light-years away in the Large Magellanic Cloud, which is a satellite galaxy of our own Milky Way galaxy. (See the box "Supernova 1987A" on the facing page.) For the first time, it was possible to look back in photographic archives at the location of the explosion and find the parent star of the supernova, which was a $20M_\odot$ blue supergiant. Because of the star's proximity and, hence, the brightness of the supernova, observations of unprecedented accuracy became possible. (It should not be overlooked that SN1987A occurred during the current "golden age" of astronomy, when numerous observatories worldwide have sophisticated equipment in place.)

Most important, however, SN1987A is the only supernova from which neutrinos were observed. Two underground detectors sensitive to electron antineutrinos, Kamiokande II in Japan and IMB in Ohio, detected bursts of twelve and eight antineutrinos, respectively, over a 10-second interval. The small number of events did not allow for detailed quantitative modeling of SN1987A, but it did provide qualitative estimates of what had happened.

The detected signal strongly supports the picture of a hot proto-neutron star forming and cooling by neutrino emission and is entirely consistent with our current theories of core collapse. The energies of individual neutrinos correspond to the expected initial temperature of a proto-neutron star, while the duration of the bursts is in line with the 10-second cooling time for such an object. The energy spectrum of the neutrinos permitted an estimate of the total energy radiated during the supernova, which is consistent with the creation of a $1.4M_\odot$ neutron star whose radius measures 15 kilometers.

At the same time, analysis of the emission spectra of SN1987A unequivocally showed that the ejected envelope was stirred up considerably during the explosion. Especially puzzling was the presence of iron in the outer hydrogen and helium layers of the ejecta, indicating that a substantial amount of mixing



Supernova 1987A
a brief photo history

On February 24, 1987, the astronomy community was startled and delighted by the appearance of a dazzling supernova in the Large Magellanic Cloud, which is a companion galaxy to our own Milky Way galaxy and is visible from the southern hemisphere. The super-bright "new star" could be easily seen by the naked eye. In the pair of photos shown at the top of the page, the arrow in the photo on the left points to a $20M_{\odot}$ blue supergiant. The photo was taken in February 1984. The photo to its right was taken on March 8 and 9, 1987, with the 3.9-meter Anglo-Australian telescope at the Anglo-Australian Observatory (in New South Wales, Australia). The star has become a supernova.

Seven years later, in the spring of 1994, the Hubble Space Telescope trained on-site its wide-field planetary camera 2 to record the three-ring structure pictured above. The rings are most likely in three parallel but separate planes that are inclined to our point of view, making the rings appear to intersect. The small, bright central ring surrounds the supernova site, and the two larger rings are presumably lying in front of and behind the site.

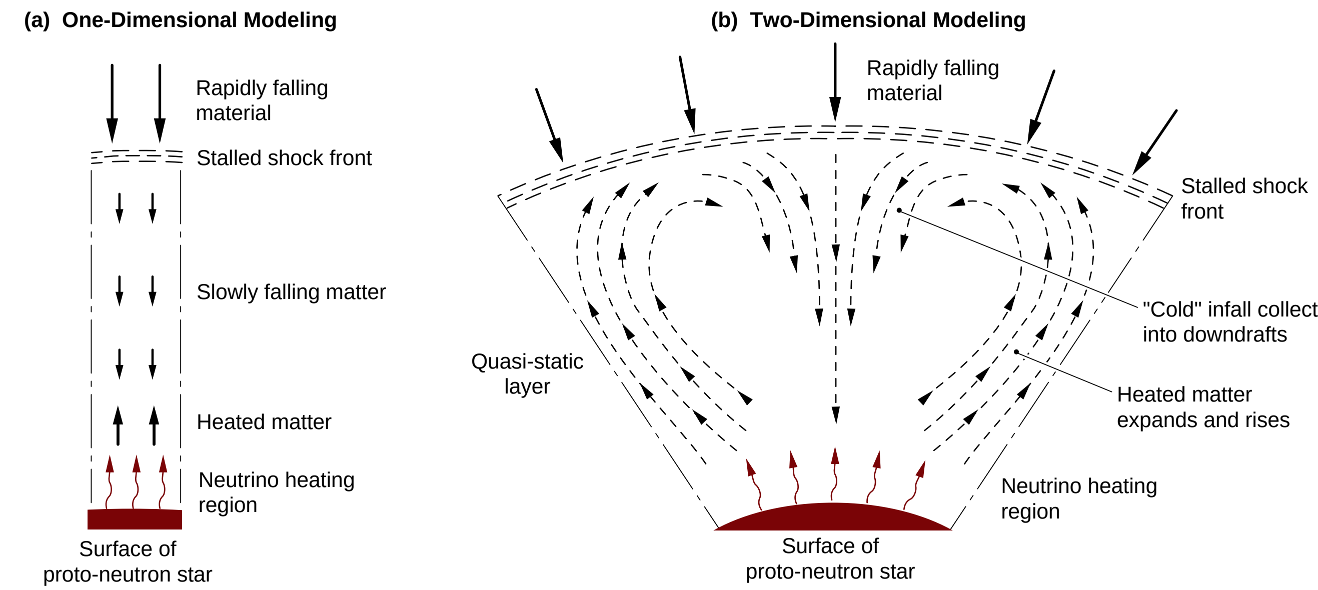


Figure 5. A Convective Engine

(a) For simplicity, supernovae were often modeled in one dimension. A star was assumed to be spherically symmetric, its radius being the only spatial parameter that mattered. Doing simulations was therefore equivalent to doing physics in a long tube, even though the transfer of heat from one end of a pipe to the other is not very effective. (b) With the advent of multidimensional models, convection could occur. Hot, buoyant material could rise in one part of the star, to be replaced by cooler material falling from some other region. An in-out circuit is established that allows for the efficient and continuous transfer of heat out of the core and into the quasi-static layer. Energy from the gravitational collapse is thus converted into mechanical work as heat is being transferred between hot and cold reservoirs. In this sense, supernovae can be thought of as being powered by a simple convective engine.

had taken place over very large distances (tens of millions of kilometers). Some of this mixing was explained by instabilities that occurred while the shock wave was running from the core to the distant surface of the star, well after the explosion had been launched. Nevertheless, these observations promoted an awareness that violent instabilities might be involved in the explosion mechanism.

This idea was not entirely new. In 1979, Richard Epstein of Los Alamos Scientific Laboratory had already proposed that instabilities at the edge of the proto-neutron star might be important. Hans Bethe later pointed out that an explosion due to neutrino heating, as in the delayed mechanism, would necessarily lead to convection because matter is "heated from below."

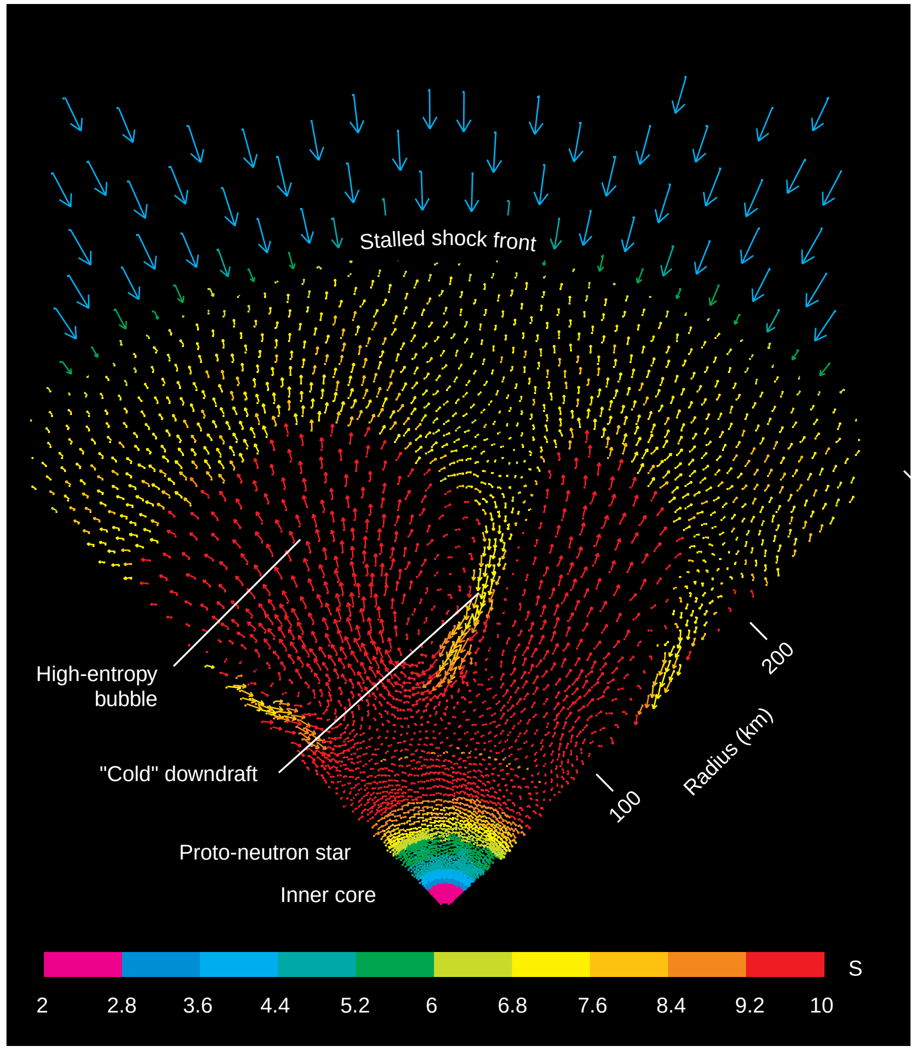
However, computer limitations and the complexity of supernova physics led most astrophysicists to simplify simulations by assuming spherical symmetry. The problem was therefore reduced to one spatial dimension—the radius. As a result, instabilities were thought to mix matter at microscopic scales; they were not thought to lead to large-scale bulk flows.

Over the years that followed the advent of SN1987A, we became convinced that to explain the observed churning of elements, one had to look into the explosion mechanism. We felt that "standard" one-dimensional modeling was likely to miss some important qualitative aspects that followed core collapse. As a result, in 1991 we started research with the goal of simulating the explosion mechanism in multidimensions. Of great help were newly available, inexpensive, powerful desktop computers on which two-dimensional and sometime three-dimensional simulations could be run.

Even from primitive, initial calculations, we noticed intense convective instabilities (akin to boiling) arising from the simultaneous existence of cold inflows and heated outflows. The convection was driven by matter made hot and buoyant by neutrino heating. Such instabilities were impossible to model by one-dimensional simulations that average quantities at a given radius (Figure 5).

Figure 6 on the next page is a snapshot of the core region 50 milliseconds after core bounce. As in other models, our postbounce shock wave is stalled and is now at a radius of about 300 kilometers. As falling matter passes through the shock front, its density increases, and its velocity decreases. The matter meets with larger and larger neutrino fluxes, is heated, and expands into large bubbles that rise through the quasi-static layer like hot-air balloons. The bubbles push against the shock. As time passes (Figure 7), more and more bubbles collect and push until the shock is finally driven outward. *The star becomes a supernova!*

Figure 6. Computer Simulation of Neutrino-Driven Convection
his graphic shows a slice of the core egion 50 milliseconds after the bounce. arcels of matter are shown as colored rrows; the length and direction of an rrow indicates velocity, and color indi- ates entropy (*S*). Regions of higher ntropy correspond to regions that have een heated. The shock front (where ellow arrows meet green arrows) lies at bout 300 kilometers. Low-entropy, high- elocity material (blue arrows) rains own on the shock, and its entropy ncreases as it moves through the front. he material becomes part of the quasi- tatic layer. Closer to the core, energetic eutrinos streaming out of the proto- eutron star (blue-green region extend- ng to about 40 kilometers) are absorbed n the quasi-static layer, which becomes eated. High-entropy bubbles (red) are lready rising. They will transfer energy o the shock front, reenergizing it and llowing it to move farther out. ow-entropy downdrafts have formed yellow filaments) that funnel cooler material toward the proto-neutron star, hus closing the convective loop.



Supernovae and Convection

Obtaining a supernova explosion is omewhat akin to blowing up an ordi- ary pressure cooker. The lid of the ooker is the ram pressure of the falling matter; the stove is a hot proto-neutron tar. Blowing up the cooker requires a uildup of pressure against the lid, which in turn depends on a good ansport of heat between the top and ottom of the cooker. It is convection hat allows heat to be carried to the d. The pressure builds up until the d finally pops.

In more physical terms, our simula- ons led us to elaborate on a new aradigm in which the supernova s viewed as a convective engine. The proto-neutron star is viewed as a heat source radiating neutrinos, and the envelope of the star is a cold reservoir. The circulation of matter and the exchange of heat allow mechanical work to be extracted from the energy liberated by the gravitational collapse (see Figure 8). This paradigm explains the failure or marginality of simula- tions in one dimension; heat transport with one pipe can hardly be effective. But in two dimensions, an in-out circuit can be established.

The transport of energy via convection has the additional feature that the explosive energies are self- limiting. Once an explosion occurs, matter is ejected and dispersed into a nebulous cloud of gas. There is no more matter left to heat, and the energy input stops. Thus, the model arrives at a natural explanation of the general constancy of explosion energies for different supernovae.

Furthermore, our simulations were very encouraging because successful explosions were obtained in a way that seemed fairly insensitive to the details of the numerical implementation of the physics. Subsequent, increasingly real- istic simulations (that is, simulations that tracked more physical processes) by us and others confirmed the key role of neutrino-driven convection in the genesis of the explosion.

Despite the success of our model, current multidimensional simulations still have significant problems.

Neutrinos and Supernovae

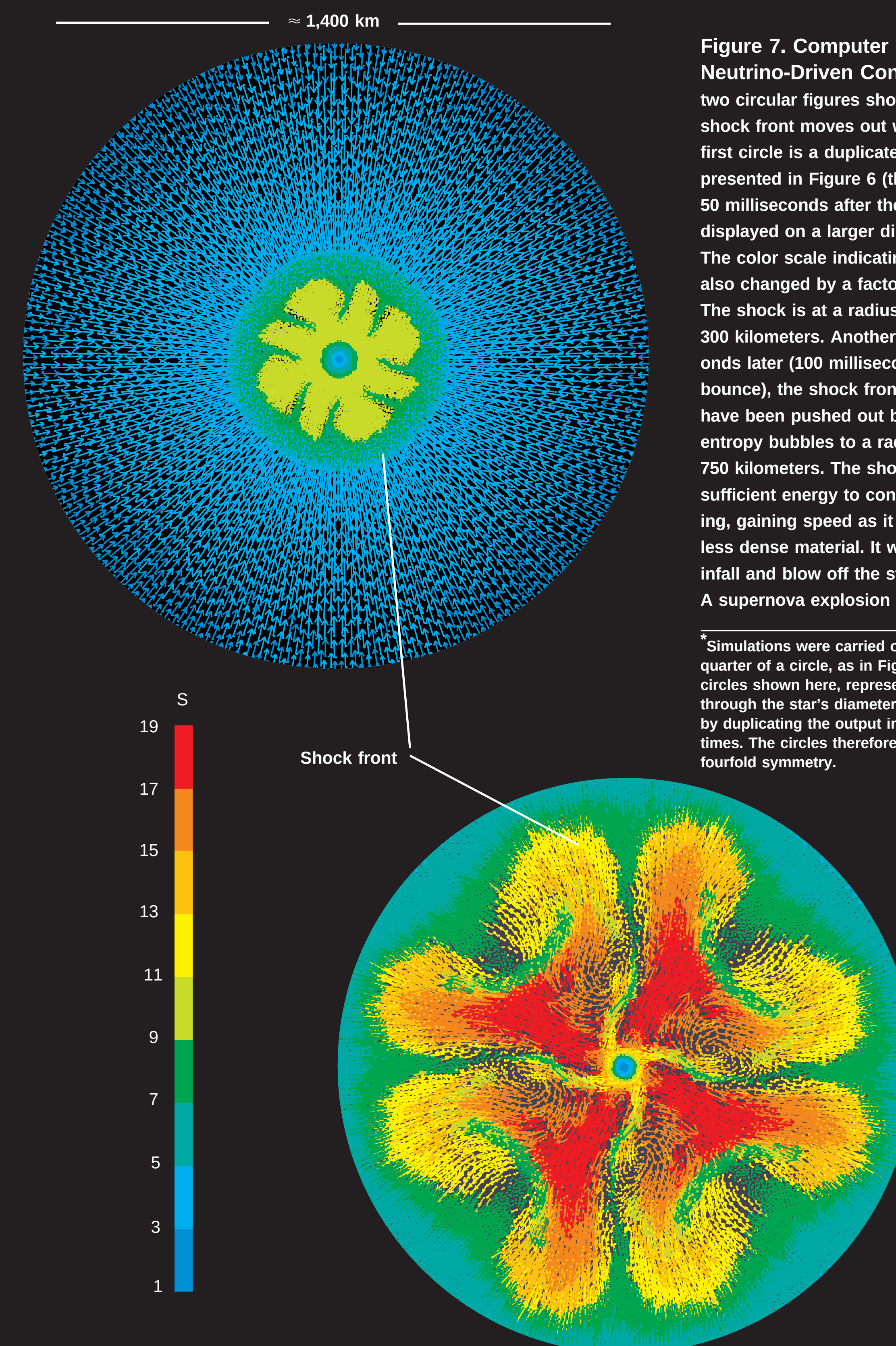
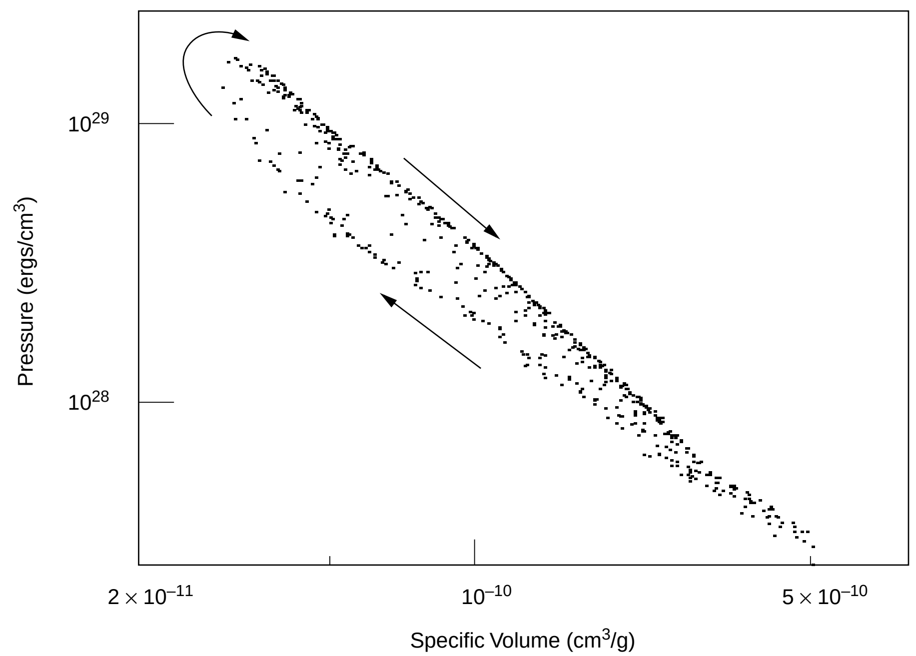


Figure 7. Computer Simulation of Neutrino-Driven Convection These two circular figures show how the shock front moves out with time. The first circle is a duplicate of the graphic presented in Figure 6 (the core region 50 milliseconds after the bounce) only displayed on a larger distance scale. The color scale indicating entropy has also changed by a factor of 2.*
The shock is at a radius of about 300 kilometers. Another 50 millisec- onds later (100 milliseconds after the bounce), the shock front is seen to have been pushed out by the high entropy bubbles to a radius of about 750 kilometers. The shock now has sufficient energy to continue propagat- ing, gaining speed as it encounters less dense material. It will reverse the infall and blow off the stellar envelope. A supernova explosion has occurred.

*Simulations were carried out in only a quarter of a circle, as in Figure 6. The full circles shown here, representing a cut through the star's diameter, were created by duplicating the output information four times. The circles therefore show an artificial fourfold symmetry.

Figure 8. A Thermodynamic Heat Cycle

hown here is the distribution of core articles involved in convection, plotted in he plane of pressure (*P*) versus specific olume (*V*) 50 milliseconds after the ounce. The particles lie along a loop that ssentially corresponds to the path they ollow over time in the *P-V* plane. ntegrating pressure versus volume round the loop yields the mechanical nergy per unit mass (the work done per ram of matter) delivered by the convec- ve engine. A crude estimate yields about foes per solar mass, or about 1.2 foes or the approximately 0.3$M_\odot$ involved in he convective cycling.



The calculated remnant neutron-star masses are too low when compared with observed masses in neutron star binaries. Also, in comparison with observed solar and terrestrial chemical bundances, the simulation has too much neutron–rich material (such as krypton) being ejected in the explosion.

Some of these problems may be due to the inevitable compromises that had to be made in order to run two- or three-dimensional versus one-dimensional simulations. For instance, he multidimensional scheme to track neutrinos had to be made considerably impler than the one-dimensional ransport algorithms. Similarly, the general relativistic corrections to lassical Newtonian gravity are more difficult to implement in multidimen- ional calculations. These limitations re gradually being overcome, and hopefully, the agreement with observa- ions will improve. Recently, however, esearchers using an improved multi-group neutrino diffusion had difficulty obtaining supernovae even after ncorporating convection. Could it be that obtaining explosions requires dditional physics?

One exciting possibility is that these discrepancies point toward the exis- ence of some new physics beyond the standard model, such as neutrino oscillations. In the MSW picture, which requires that neutrinos have mass, the enhanced oscillation of one neutrino species into another is triggered by the passage of the neutrino through matter of a certain density. (See the article "MSW" on page 156). Considering that, at the time of collapse, the densities in supernova range all the way from 10^{14} to 10^{-5} g/cm^3, it is clear that, should neutrinos oscillate, they will most probably do so during supernova explosions.

Of great interest is the density range between 10^{12} and 10^7 g/cm^3. The first density corresponds to the surface of the proto-neutron star, where neutrinos stop diffusing and start free-streaming. The second density corresponds to the outer edge of the neutrino heating region outside the proto-neutron star. Because electron neutrinos are most easily absorbed by nucleons, they are the most efficient at heating. One can envision that tau or muon neutrinos created within the proto-neutron star might oscillate into electron neutrinos between the emission and absorption regions, which would result in more heating than currently predicted. The converse may also be true—electron neutrinos are lost through oscillations; hence, the heating is reduced. In short, if neutrino oscillations exist, they could have an important impact on the dynamics of the explosion.

The Last Word

One further significance of the neutrino signal from SN1987A is that it placed a new limit on the mass of the electron neutrino. The speed of a massive particle depends on its mass and energy. Because each neutrino let loose by SN1987A traversed the same 170,000 light-years in reaching Earth, one can use the measured spread in neutrino energies and in arrival times to deduce the speed and hence to constrain the neutrino mass. The result is less than 10 electron volts, slightly better than prior experimental limits.

Neutrino and supernova physics are intimately linked. It is therefore not surprising that one of the dearest wishes of astronomers and neutrino physicists alike is for a supernova to occur within our own galaxy. If such an explosion were to take place, it is estimated that the new, large neutrino detectors would register several thousand events. This would provide us with a detailed picture of the events that accompany the collapse of the core, a picture that is otherwise shielded from our view by the opaque envelope of the star. Moreover, an intense neutrino signal would provide clues and constraints on neutrino oscillations or other physical processes that we may not have imagined yet. It is in part the prospect of such serendipitous discoveries that promises to make the field of supernova and neutrino astrophysics an exciting one for years to come. ■

Further Reading

Benz, W., S. A. Colgate, and M. Herant. 1994. Supernova Explosions and Hydrodynamic Instabilities: From Core Bounce to 90 Days. *Physica D* **77**: 305.

Bethe, H. A. 1990. Supernova Mechanism. *Reviews of Modern Physics* **62**: 801.

Burrows, A., D. Klein, and R. Gandhi. 1992. The Future of Supernova Neutrino Detection. *Physical Review D* **45** (5): 3361.

Colgate, S. A., and M. H. Johnson. 1960. Hydrodynamic Origin of Cosmic Rays. *Physical Review Letters* **5**: 235.

Colgate, S. A., and R. H. White. 1966. Hydrodynamic Behavior of Supernovae Explosions. *Astrophysical Journal* **143**: 626.

Epstein, R. I., Monthly Notices of the Royal Astronomical Society **188**: 305.

Herant, M., W. Benz, W. R. Hix, et al. 1994. Inside the Supernova: A Powerful Convective Engine. *Astrophysical Journal* **435**: 339.

Tubbs, D. L., and D. N. Schramm. 1975. Neutrino Opacities at High Temperatures and Densities. *Astrophysical Journal* **201** (2): 467.

Cantrella, J. M., et al., Eds. 1985. *Numerical Astrophysics*. Boston: Jones & Bartlett.

Woosley, S. E., et al. 1994. The R-Process and Neutrino Heated Supernova Ejecta. *Astrophysical Journal* **433**: 229.

Woosley, S. E. 1996. Nucleosynthesis in Supernovae. *Astronomical Society of the Pacific Conference Series* **99**: 253.

Marc Herant received a B.S. in physics from Caltech. Despite some equivocating about the relative merits of exploring the world and scientific research, Marc entered graduate school in astronomy at Harvard University. After sticking his fingers in a variety of projects, he finally settled on writing a Ph.D. thesis on the hydrodynamics of supernova 1987A (SN1987A) under the benign supervision of his advisor, Willy Benz. He then took advantage of a NASA-sponsored Gamma–Ray Observatory Postdoctoral Fellowship to extend his research on supernovae with Stan Woosley at the University of California, Santa Cruz. This fellowship was followed in 1994 by a Director Postdoctoral Fellowship at Los Alamos, where Marc was able to indulge in his interest in the life sciences by studying the mechanics of cell motility. Marc now lives with his wife Debra in St. Louis, Missouri, where he is a second-year medical student at Washington University.

Stirling A. Colgate earned his B.S. and Ph.D. degrees in physics from Cornell University in 1948 and 1952, respectively. He was a staff physicist at Lawrence Livermore Laboratory for twelve years and then president of New Mexico Institute of Mining and Technology for ten years, where he remains an Adjunct Professor. In 1976, he joined the Theoretical Division at the Laboratory and in 1980 became leader of the Theoretical Astrophysics Group. His research interests include nuclear physics, astrophysics, plasma physics, atmospheric physics, inertial fusion, geotectonic engineering, and the epidemiology of AIDS. Colgate has been involved in nuclear weapons testing, has participated in negotiations on nuclear testing for the U.S. State Department, and has had a leading role in magnetic fusion. His early work on supernovae led to the understanding of early neutrino emission from neutron stars—since then confirmed by SN1987A. In 1981, Colgate was named a Senior Fellow at the Laboratory and is an active member of the U.S. National Academy of Sciences.

Willy Benz is a professor of astronomy and planetary sciences at the University of Arizona, where he holds a joint appointment with Steward Observatory and the Lunar and Planetary Laboratory. He studied physics and earned a Ph.D. in astrophysics from Geneva University, Switzerland. Benz came to the United States in 1984 and joined the Laboratory as a postdoctoral fellow. In 1986, he moved to Harvard University as an assistant professor before joining the ranks of the faculty of the University of Arizona in 1991. Even though Benz left Los Alamos more than a decade ago, he has pursued scientific collaborations with several groups at the Laboratory as well as served as an occasional consultant. His research interests lie in the understanding of violent astrophysical phenomena ranging from dynamical fracture of brittle solids, collisions between planets and between stars, to supernova explosions. Benz has also been involved in investigating the collisional evolution of the early solar system, the origin of the moon, and more recently, the role of large-scale convection in supernova explosions.

Chris Fryer received his B.A. in mathematics and astrophysics at the University of California at Berkeley under the tutelage of Alex Filippenko. Unbeknownst to Fryer, that association sealed his fate. Almost immediately upon his arrival at the University of Arizona to pursue graduate work, he began working on supernovae with Willy Benz, who erroneously assumed that any student of Alex Filippenko's must necessarily want to work on such topics. Working on supernova and neutron-star projects naturally led to the acquisition of an additional advisor, Stirling Colgate. It also led to many "character-building" summers at Los Alamos. Fryer received his Ph.D. early in 1997 and is currently a postdoctoral fellow at the University of California at Santa Cruz, where he is working with Stan Woosley on supernovae, gamma-ray bursts, and neutron stars.