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 $10^{20}$ 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 ejected 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.

This pivotal and wondrous function of the neutrino, so much in contrast with its usual marginal position, received triumphal 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 supernova 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 entirely 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 at 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

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A Star's Life

A star performs one of nature's finest high-wire acts. It carefully and ostinately maintains its balance against the omnipotent pull of gravity. It is gravity that shapes a primordial cloud of gas into a spherical tar, and it is gravity that collapses and compresses the gas. Compression, however, increases both the temperature and the internal pressure of the gas. Once that pressure is sufficient to counteract gravity's pull, the star stops shrinking. If for some reason the internal pressure temporarily exceeds the gravitational force, the star will expand.

The primordial gas consists of hydrogen, some helium, and traces of other light elements. This atmosphere in the form of ions for minutes after the Big Bang. See the article "Dark Matter and Massive Neutrinos" on page 180 for more details.

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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 thermonuclear 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 equilibrium. 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.

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, and 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 temperature 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 burning.

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 heavier, 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 time it takes for a star to burn its fuel decreases rapidly as its mass increases. Compared with the lighter cousins, massive stars are squashed 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☉ 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. However, the gas is mostly 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, and 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 temperature 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 burning.

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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 (\(\nu_e\)). The neutron escapes from the core and releases 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, as written as \((N, Z)\), the two-step process is represented by the following reactions:

\[
\begin{align*}
(N, Z) + e^- &\rightarrow (N - 1, Z - 1) + \nu_e \\
(N - 1, Z - 1) &\rightarrow (N, Z) + e^- + \nu_e
\end{align*}
\]

During a confluence 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 drain energy from a star. The two physicists probably dubbed this set of the reactions the Urca process.

Although a heavy star will burn hydrogen and helium for many millions of years, it will burn carbon for about 0.0001 years and oxygen for only 0.0000000000001 years. Incredibly, silicon burning lasts but one day. Silicon fuses to become iron, but once iron is created, the process of liberating energy through thermonuclear fusion comes to an abrupt end. Iron is the most stable of all nuclei. Any union or fission reactions in which iron participates absorb rather than release energy. Thus, formation of the iron core marks the beginning of the end for massive stars. As energy continues to eke out, the core pressure drops, and the core rapidly loses its internal support. The core physically implodes as gravity creates the planet-sized center of collapse under its own weight. As discussed in the next section, the ejection of silicon and heavier elements is initiated.

The Core Collapse

Just prior to its collapse, the silicon-iron core has a radius of about 40 kilometers and a mass of about 1.4\(M_\odot\). 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 underlies that work, as nuclear absorption of a photon breaks the iron apart and sucksth energy from the central core.

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.

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 squashed together.

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, degenerate pushes electron energies above the 2.25 MeV threshold of the electron capture process. In the end, it is the growing pressure from the degenerate nucleon gas, termed about 10^{24}g/cm^3, that ultimately halts the collapse of the core.

An Exotic State

The incredibly dense states 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 these states always have higher energies. In the supernova core, the degeneracy energy of the gas is enormous—much higher than the thermal energy. Because these arguments also apply to neutron 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.

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

Neutrinos and Supernovae

Neutrinos play a critical role in the formation of supernovae. That role is called the neutrino-neutron star, which even more about 10^7 MeV of energy needed to transform free, unbound protons (p) into neutrons (n):

\[ p + e^- \rightarrow n + \nu_e. \]
Neutrinos and Supernovae

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 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 became neutralized by the kinetic energy of the debris. Based on observations, the explosive energies of supernovae typically tally to about 10^45 ergs, or 1 “foe.” Hans Bethe coined the acronym for (ten to the) 51 ergs, or 1 “foe.”

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 computer 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. 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 as the mechanism responsible for the high energies found in core-collapse 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, and 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* boson. Thus, there is no change in the charge states of the participants. Instead, a neutrino could merely scatter from nucleons or electrons—experimentally, Oppenheimer and Schwarzschild found neutral-current interactions 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:

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

Neutrinos 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 scatter via neutral-current interactions, so that $\nu_e$, $\nu_\mu$, and $\nu_\tau$, produced as the core collapses, are also trapped.

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 models, efforts to obtain explosions were frequently thwarted. Stellar fizzes 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 afterward. Wilson’s simulations ran from the start of core collapse to about half a second after the bounce. In his simulations, apparent fizzes 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 collapses 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 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 leaving 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 from Earth. As the first supernova seen in 1987, it was of great interest to many astrophysicists. 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 hypothesis that 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 temperature of 1.4 $M_\odot$ neutron star whose radius measures 15 kilometers.

At the same time, the 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 mixed elements of oxygen, nitrogen, and helium layers of the ejecta, indicating that a substantial amount of mixing.
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 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 supernova 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 multidimensional models, which average quantities at a given radius (Figure 5).

Figure 5. A Convective Engine
(a) One-Dimensional Modeling
(b) Two-Dimensional Modeling

Supernova 1987A

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.

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 supernova 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 multidimensional models, which 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

The graphic shows a slice of the core region 50 milliseconds after the bounce. Arcs of matter are shown as colored rows; the length and direction of an arrow indicates velocity, and color indicates entropy. Regions of higher entropy correspond to regions that have been heated. The shock front (where yellow arrows meet green arrows) lies at about 300 kilometers. Low-entropy, high-entropy material (blue arrows) rains down on the shock, and its entropy increases as it moves through the front. Heat transport is carried to the top through convection, which becomes heated. High-entropy bubbles (red) are being heated. They will transfer energy to the shock front, reenergizing it and allowing it to move farther out. Downdrafts have formed yellow filaments; funnel cooler material toward the proto-neutron star, thus closing the convective loop.

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 milliseconds 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 propagating, 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.

**Supernovae and Convection**

Obtaining a supernova explosion is somewhat akin to blowing up an ordinary pressure cooker. The lid of the cooker is the ram pressure of the falling matter; the stove is a hot proto-neutron star. Blowing up the cooker requires a buildup of pressure against the lid, which in turn depends on a good heat transport from the top and bottom of the cooker. It is convection that allows heat to be carried to the lid. The pressure builds up until the lid finally pops.

In more physical terms, our simulations led us to elaborate on a new paradigm in which the supernova is 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 simulations 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 realistic 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.
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 abundances, 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, the multidimensional scheme to track neutrinos had to be made considerably simpler than the one-dimensional transport algorithms. Similarly, the general relativistic corrections to classical Newtonian gravity are more difficult to implement in multidimensional calculations. These limitations re gradually being overcome, and hopefully, the agreement with observations will improve. Recently, however, researchers using an improved multi-group neutron diffusion had difficulty obtaining supernovae even after incorporating convection. Could it be that obtaining explosions requires additional physics? One possible possibility is that these discrepancies point toward the existence 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 neutrinos through matter of a certain density. (See the article “MSW” on page 156). Considering that, at the time of collapse, the densities in supernovae range all the way from \(10^{3} \text{ g/cm}^3\) to \(10^{7} \text{ g/cm}^3\), it is clear that, should neutrinos oscillate, they will most probably do so during supernova explosions.

Of great interest is the density range between \(10^{12} \text{ g/cm}^3\) and \(10^3 \text{ g/cm}^3\). 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 during 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 to Earth, 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 as with a detailed picture of the events that accompany the collapse of the core, a picture that is otherwise shrouded 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 phenomena 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.