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ARTICLES

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How a Supernova Explodes

When a large star runs out of nuclear fuel, the core collapses in milliseconds. The subsequent "bounce" of the core generates a shock wave so intense that it blows off most of the star's mass

by Hans A. Bethe and Gerald Brown

The death of a large star is a sudden and violent event. The star evolves peacefully for millions of years, passing through various stages of development, but when it runs out of nuclear fuel, it collapses under its own weight in less than a second. The most important events in the collapse are over in milliseconds. What follows is a supernova, a prodigious explosion more powerful than any since the big bang with which the universe began.

A single exploding star can shine brighter than an entire galaxy of several billion stars. In the course of a few months it can give off as much light as the sun emits in a billion years. Furthermore, light and other forms of electromagnetic radiation represent only a small fraction of the total energy of the supernova. The kinetic energy of the exploding matter is 10 times greater. Still more energy—perhaps 100 times more than the electromagnetic emission—is carried away by the massless particles called neutrinos, most of which are emitted in a flash that lasts for about a second. When the explosion is over, most of the star's mass has been scattered into space, and all that remains at the center is a dense, dark cinder. In some cases even that may disappear into a black hole.

Such an outline description of a supernova could have been given almost 30 years ago, and yet the detailed sequence of events within the dying star is still not known with any certainty. The basic question is this: A supernova begins as a collapse, or implosion; how does it come about, then, that a major part of the star's mass is expelled? At some point the inward movement of stellar material must be stopped and then reversed; an *im*plosion must be transformed into an *ex*plosion.

Through a combination of computer simulation and theoretical analysis a coherent view of the supernova mechanism is beginning to emerge. It appears the crucial event in the turnaround is the formation of a shock wave that travels outward at 30,000 kilometers per second or more.

Supernovas are rare events. In our own galaxy just three have been recorded in the past 1,000 years; the brightest of these, noted by Chinese observers in 1054, gave rise to the expanding shell of gas now known as the Crab Nebula. If only such nearby events could be observed, little would be known about supernovas. Because they are so luminous, however, they can be detected even in distant galaxies, and 10 or more per year are now sighted by astronomers.

The first systematic observations of distant supernovas were made in the 1930's by Fritz Zwicky of the California Institute of Technology. About half of the supernovas Zwicky studied fitted a quite consistent pattern: the luminosity increased steadily for about three weeks and then declined gradually over a period of six months or more. He designated the explosions in this group Type I. The remaining supernovas were more varied, and Zwicky divided them into four groups; today, however, they are all grouped together as Type II. In Type I and Type II supernovas the events leading up to the explosion are thought to be quite different. Here we shall be concerned primarily with Type II supernovas.

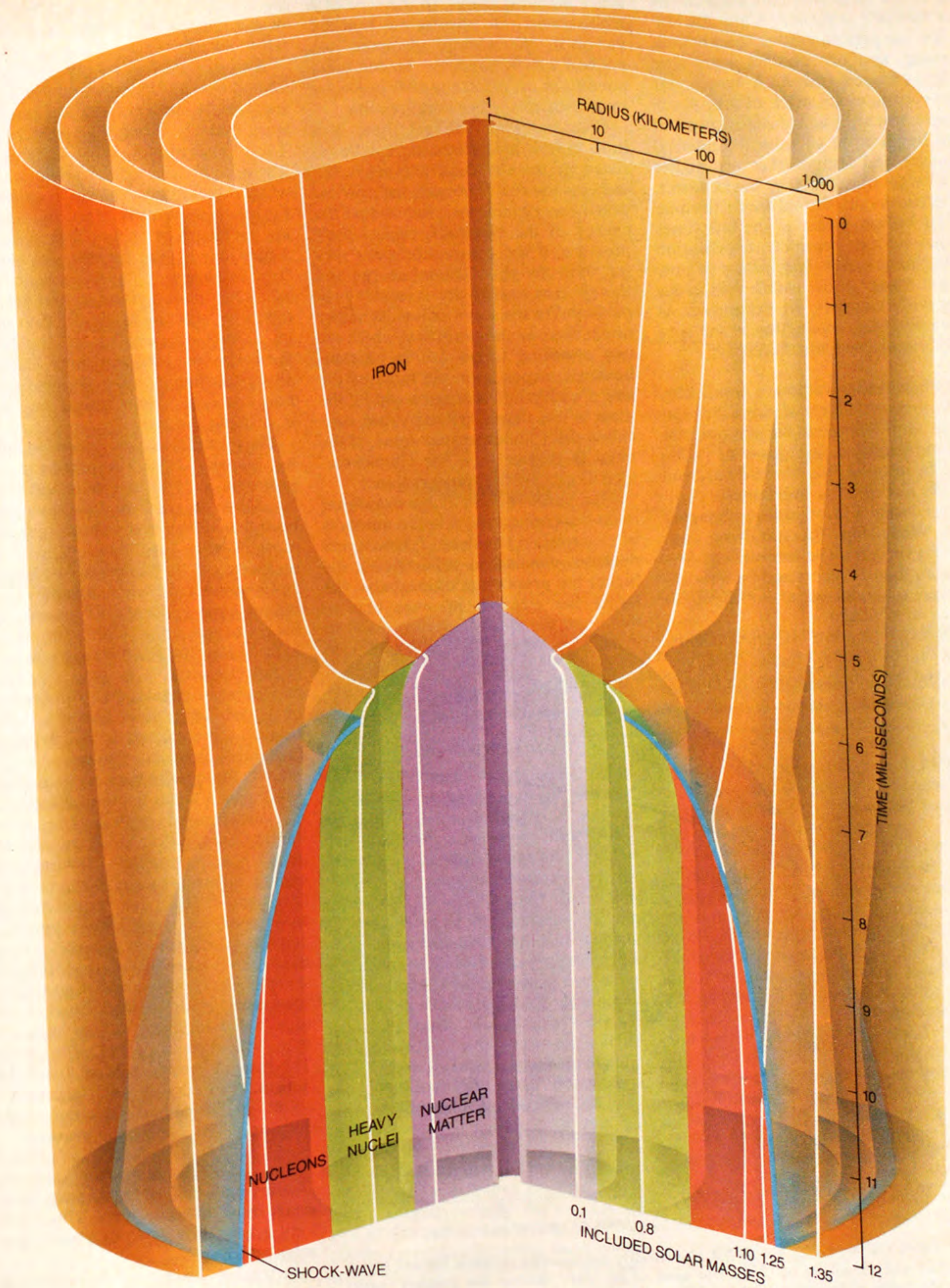
The basis for the theory of supernova explosions was the work of Fred Hoyle of the University of Cambridge. The theory was then developed in a fundamental paper published in 1957 by E. Margaret Burbidge, Geoffrey R. Burbidge and William A. Fowler, all of Caltech, and Hoyle. They proposed that when a massive star reaches the end of its life, the stellar core collapses under the force of its own gravitation. The energy set free by the collapse expels most of the star's mass, distributing the chemical elements formed in the course of its evolution throughout interstellar space. The collapsed core leaves behind a dense remnant, in many cases a neutron star.

A supernova is an unusual and spectacular outcome of the sequence of nuclear fusion reactions that is the life history of a star. The heat given off by the fusion creates pressure, which counteracts the gravitational attraction that would otherwise make the star collapse. The first series of fusion reactions have the net effect of welding four atoms of hydrogen into a single atom of helium. The process is energetically favorable: the mass of the helium atom is slightly less than the combined masses of the four hydrogen atoms, and the energy equivalent of the excess mass is released as heat.

The process continues in the core of the star until the hydrogen there is used up. The core then contracts, since gravitation is no longer opposed by energy production, and as a result both the core and the surrounding material are heated. Hydrogen fusion then begins in the surrounding layers. Meanwhile the core becomes hot enough to ignite other fusion reactions, burning helium to form carbon, then burning the carbon to form neon, oxygen and finally silicon. Again each of these reactions leads to the release of energy. One last cycle of fusion combines silicon nuclei to form iron, specifically the common iron isotope ^{56}Fe, made up of 26 protons and 30 neutrons. Iron is the end of the line for spontaneous fusion. The ^{56}Fe nucleus is the most strongly bound of all nuclei, and further fusion would absorb energy rather than releasing it.

At this stage in the star's existence it has an onionlike structure. A core of iron and related elements is surrounded by a shell of silicon and sulfur, and beyond this are shells of oxygen, carbon and helium. The outer envelope is mostly hydrogen.

Only the largest stars proceed all the



COLLAPSE AND REBOUND are the initiating events in a supernova explosion. Here the core of a massive star is shown as it passes through the moment of "maximum scrunch," when the center reaches its highest density. Each contour represents a shell of matter whose radial position is followed through a period of 12 milliseconds. The included mass, or total mass inside the contour, does not change as the shells contract and expand. Initially the core is iron, but the extreme compression of the collapse converts the innermost few kilometers into nuclear matter, the stuff of the atomic nucleus. Surrounding this region is a shell made up of various heavy nuclei, including iron. At maximum scrunch the contraction stops with a jolt, creating a shock wave (*blue line*) that travels outward at 30,000 kilometers per second or more. In the wake of the shock nuclei are broken up into individual nucleons (protons and neutrons).

way to the final, iron-core stage of the evolutionary sequence. A star the size of the sun gets no further than helium burning, and the smallest stars stop with hydrogen fusion. A larger star also consumes its stock of fuel much sooner, even though there is more of it to begin with; because the internal pressure and temperature are higher in a large star, the fuel burns faster. Whereas the sun should have a lifetime of 10 billion years, a star 10 times as massive can complete its evolution 1,000 times faster. Regardless of how long it takes, all the usable fuel in the core will eventually be exhausted. At that point heat production in the core ends and the star must contract.

When fusion ends in a small star, the star slowly shrinks, becoming a white dwarf: a burned-out star that emits only a faint glow of radiation. In isolation the white dwarf can remain in this state indefinitely, cooling gradually but otherwise changing little. What stops the star from contracting further? The answer was given more than 50 years ago by Subrahmanyan Chandrasekhar of the University of Chicago.

Loosely speaking, when ordinary matter is compressed, higher density is achieved by squeezing out the empty space between atoms. In the core of a white dwarf this process has reached its limit: the atomic electrons are pressed tightly together. Under these conditions the electrons offer powerful resistance to further compression.

Chandrasekhar showed there is a limit to how much pressure can be resisted by the electrons' mutual repulsion. As the star contracts, the gravitational energy increases, but so does the energy of the electrons, raising their pressure. If the contraction goes very far, both the gravitational energy and the electron energy are inversely proportional to the star's radius. Whether or not there is some radius at which the two opposing forces are in balance, however, depends on the mass of the star. Equilibrium is possible only if the mass is less than a critical value, now called the Chandrasekhar mass. If the mass is greater than the Chandrasekhar limit, the star must collapse.

The value of the Chandrasekhar mass depends on the relative numbers of electrons and nucleons (protons and neutrons considered collectively): the higher the proportion of electrons, the larger the electron pressure and so the larger the Chandrasekhar mass. In small stars where the chain of fusion reactions stops at carbon the ratio is approximately 1/2 and the Chandrasekhar mass is 1.44 solar masses. This is the maximum stable mass for a white dwarf.

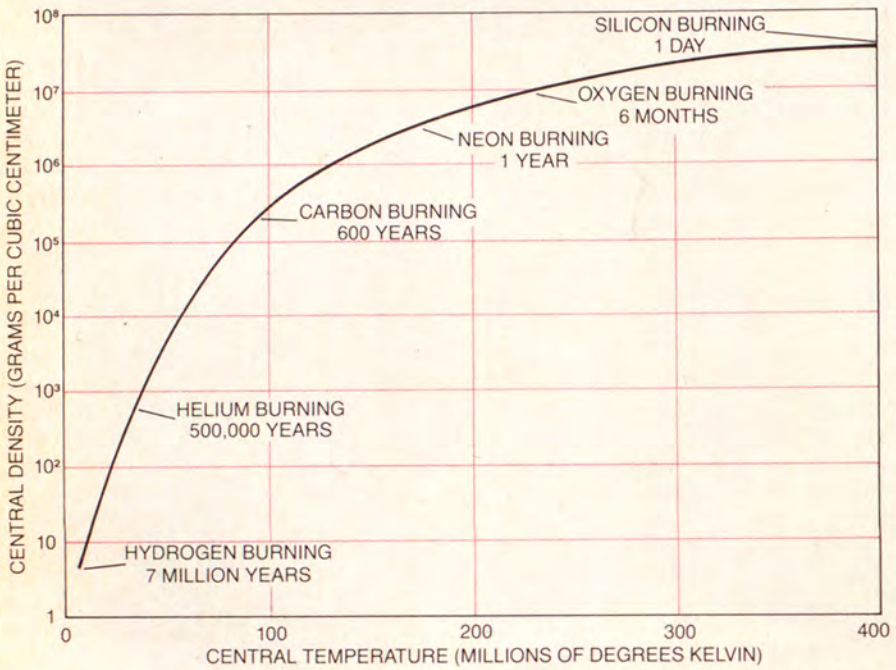
A white dwarf with a mass under the Chandrasekhar limit can remain stable indefinitely; nevertheless, it is just such stars that are thought to give rise to Type I supernovas. How can this be? The key to the explanation is that white dwarfs that explode in supernovas are not solitary stars but rather are members of binary star systems. According to one hypothesis, matter from the binary companion is attracted by the intense gravitational field of the dwarf star and gradually falls onto its surface, increasing the mass of the carbon-and-oxygen core. Eventually the carbon ignites at the center and burns in a wave that travels outward, destroying the star.

The idea that explosive carbon burning triggers Type I supernovas was proposed in 1960 by Hoyle and Fowler. More detailed models have since been devised by many astrophysicists, most notably Icko Iben, Jr., and his colleagues at the University of Illinois at Urbana-Champaign. Recent calculations done by Ken'ichi Nomoto and his colleagues at the University of Tokyo suggest that the burning is actually not explosive. The wave of fusion reactions propagates like the burning of a fuse rather than like the explosion of a firecracker; it is a deflagration rather than a detonation.

Even though the burning is less violent than a detonation, the white dwarf is completely disrupted. The initial binding energy that holds the star together is approximately 10^{50} ergs; the energy released by the burning is 20 times greater (2×10^{51} ergs), enough to account for the 10,000-kilometer-per-second velocity of supernova remnants. In the course of the deflagration nuclear reactions create about one solar mass of the unstable nickel isotope ^{56}Ni, which decays into ^{56}Co and then ^{56}Fe over a period of months. The rate of energy release from the radioactive decay is just right to account for the gradually declining light emission from Type I supernovas.

The Type II supernovas that are our main concern here arise from much more massive stars. The lower limit is now thought to be about eight solar masses.

In tracing the history of a Type II supernova it is best to begin at the moment when the fusion of silicon nuclei to form iron first becomes possible at the center of the star. At this point the star has already passed through stages of burning hydrogen, helium, neon, carbon and oxygen, and it has the onionlike structure described above.



EVOLUTION OF A MASSIVE STAR is a steadily accelerating progress toward higher temperature and density in the core. For most of the star's lifetime the primary energy source is the fusion of hydrogen nuclei to form helium. When the hydrogen in the core is exhausted, the core contracts, which heats it enough to ignite the fusion of helium into carbon. This cycle then repeats, at a steadily increasing pace, through the burning of carbon, neon, oxygen and silicon. The final stage of silicon fusion yields a core of iron, from which no further energy can be extracted by nuclear reactions. Hence the iron core cannot resist gravitational collapse, leading to a supernova explosion. The sequence shown is for a star of 25 solar masses. Data in this illustration and the one on the opposite page are based on calculations done by Thomas A. Weaver of the Lawrence Livermore National Laboratory.

The star has taken several million years to reach this state. Subsequent events are much faster.

When the final fusion reaction begins, a core made up of iron and a few related elements begins to form at the center of the star, within a shell of silicon. Fusion continues at the boundary between the iron core and the silicon shell, steadily adding mass to the core. Within the core, however, there is no longer any production of energy by nuclear reactions; the core is an inert sphere under great pressure. It is thus in the same predicament as a white dwarf: it can resist contraction only by electron pressure, which is subject to the Chandrasekhar limit.

Once the fusion of silicon nuclei begins, it proceeds at an extremely high rate, and the mass of the core reaches the Chandrasekhar limit in about a day. We noted above that for a white dwarf the Chandrasekhar mass is equal to 1.44 solar masses; for the iron core of a large star the value may be somewhat different, but it is probably in the range between 1.2 and 1.5 solar masses.

When the Chandrasekhar mass has been attained, the pace speeds up still more. The core that was built in a day collapses in less than a second. The task of analysis also becomes harder at this point, so that theory relies on the assistance of computer simulation. Computer programs that trace the evolution of a star have been developed by a number of workers, including W. David Arnett of the University of Chicago and a group at the Lawrence Livermore National Laboratory led by Thomas A. Weaver of that laboratory and Stanford Woosley of the University of California at Santa Cruz. They are the "burners" of stars; we and our colleagues in theoretical physics are "users" of their calculations.

The simulations furnish us with a profile of the presupernova core, giving composition, density and temperature as a function of radius. The subsequent analysis relies on applying familiar laws of thermodynamics, the same laws that describe such ordinary terrestrial phenomena as the working of a heat engine or the circulation of the atmosphere.

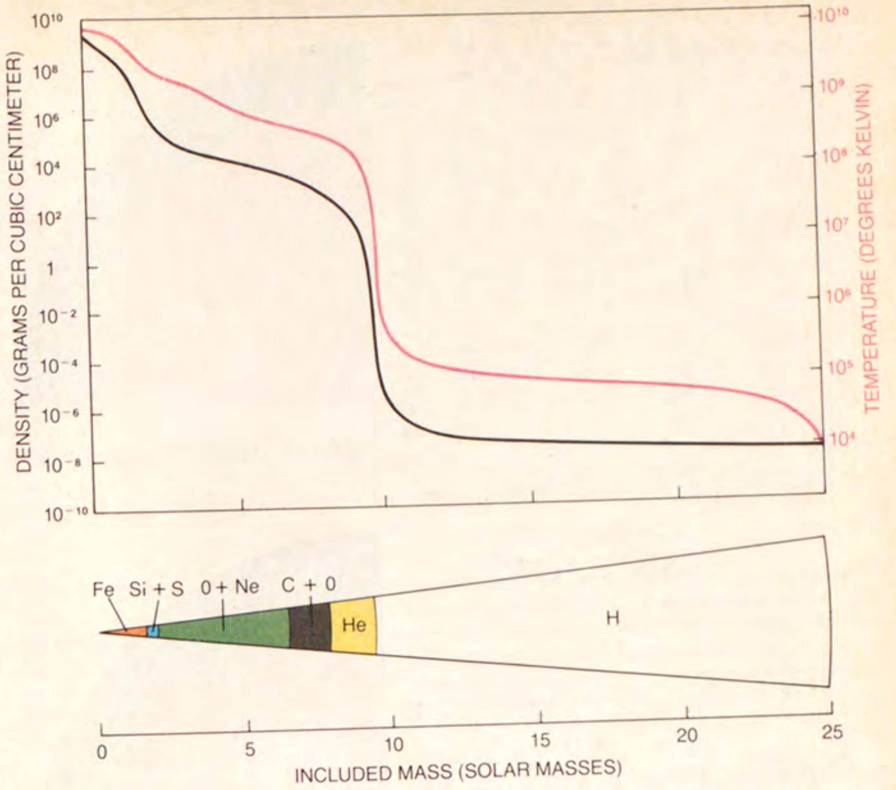
It is worthwhile tracing in some detail the initial stages in the implosion of the core. One of the first points of note is that compression raises the temperature of the core, which might be expected to raise the pressure and slow the collapse. Actually the heating has just the opposite effect.

Pressure is determined by two factors: the number of particles in a system and their average energy. In the core both nuclei and electrons contribute to the pressure, but the electron component is much larger. When the core is heated, a small fraction of the iron nuclei are broken up into smaller nuclei, increasing the number of nuclear particles and raising the nuclear component of the pressure. At the same time, however, the dissociation of the nuclei absorbs energy; since energy is released when an iron nucleus is formed, the same quantity of energy must be supplied in order to break the nucleus apart. The energy comes from the electrons and decreases their pressure. The loss in electron pressure is more important than the gain in nuclear pressure. The net result is that the collapse accelerates.

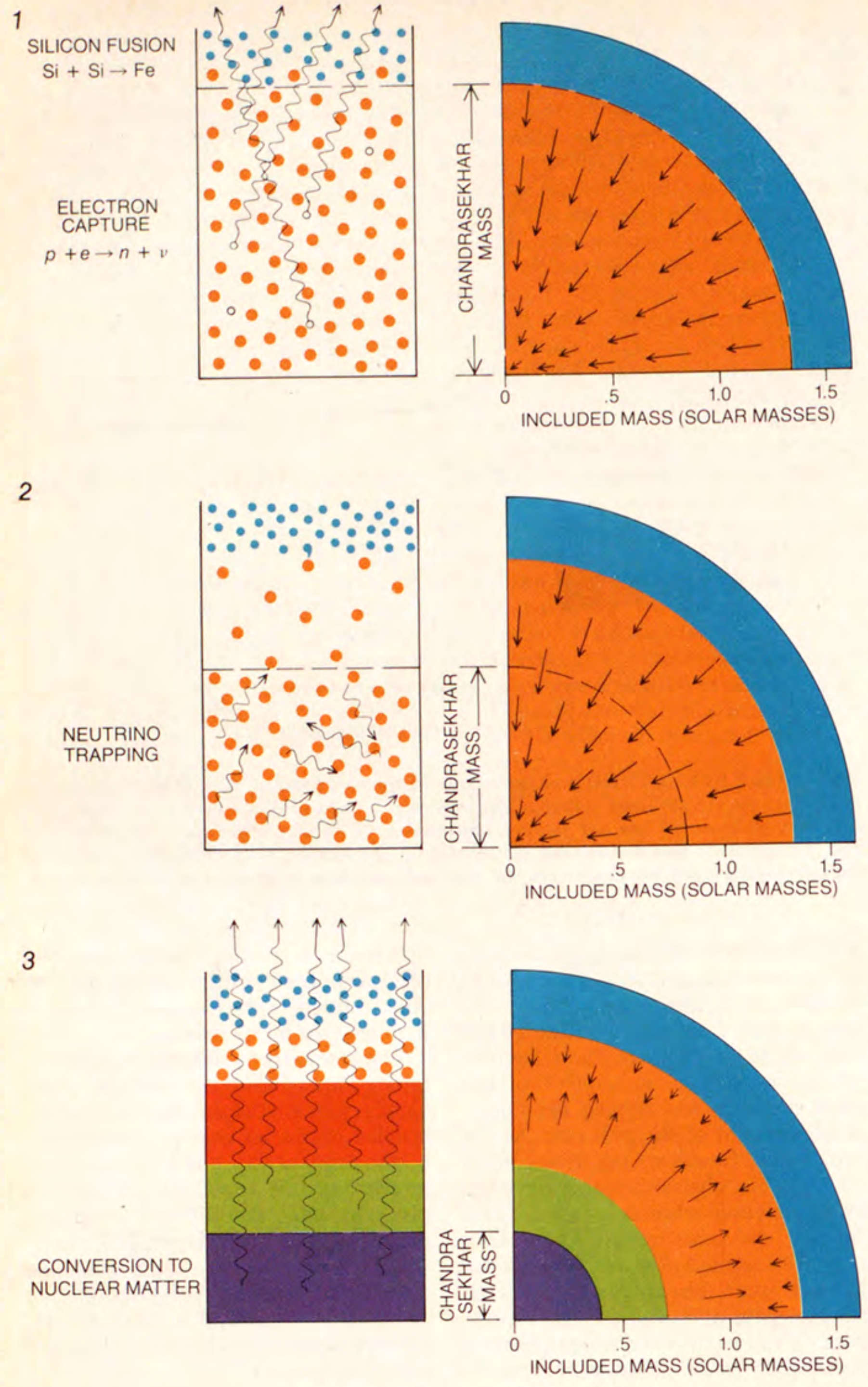
It might seem that the implosion of a star would be a chaotic process, but in fact it is quite orderly. Indeed, the entire evolution of the star is toward a condition of greater order, or lower entropy. It is easy to see why. In a hydrogen star each nucleon can move willy-nilly along its own trajectory, but in an iron core groups of 56 nucleons are bound together and must move in lockstep. Initially the entropy per nucleon, expressed in units of Boltzmann's constant, is about 15; in the presupernova core it is less than 1. The difference in entropy has been carried off during the evolution of the star by electromagnetic radiation and toward the end also by neutrinos.

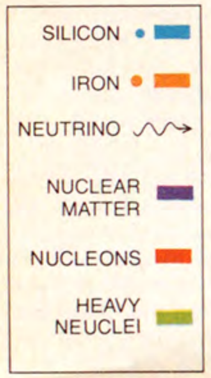
The low entropy of the core is maintained throughout the collapse. Nuclear reactions continually change the species of nuclei present, which one might think could lead to an increase in entropy; the reactions are so fast, however, that equilibrium is always maintained. The collapse takes only milliseconds, but the time scale of the nuclear reactions is typically from 10^{-15} to 10^{-23} second, so that any departure from equilibrium is immediately corrected.

Another effect was once thought to increase the entropy, but it now seems likely that it actually reduces it somewhat. The high density in the collapsing core favors the reaction known as electron capture. In this process a proton and an electron come together to yield a neutron and a neutrino. The neutrino escapes from the star, carrying off both energy and entropy and cooling the system just as the evaporation of moisture cools the body. There are several complications to this process, so that its effect on the entropy is uncertain. In any case, the loss of the electron diminishes the electron pres-



ONIONLIKE STRUCTURE is characteristic of a massive star at the end of its evolution, just before the gravitational collapse. The iron core is embedded in a mantle of silicon, sulfur, oxygen, neon, carbon and helium, surrounded by an attenuated envelope of hydrogen. Temperature and density fall off steadily in the mantle, then drop precipitously at the envelope. Fusion has stopped in the core but continues at boundaries between layers.





COLLAPSE OF THE STELLAR CORE begins when the mass of iron exceeds the Chandrasekhar mass, which is between 1.2 and 1.5 solar masses. At this point the pressure of electrons can no longer resist gravitational contraction. Early in the collapse (*1*) the inward movement is accelerated by electron capture, which converts a proton and an electron into a neutron and a neutrino. The loss of the electron reduces the electron pressure and hence the Chandrasekhar mass. When the density reaches 4×10^{11} grams per cubic centimeter (*2*), matter becomes opaque to neutrinos, which are therefore trapped in the core. By this time the Chandrasekhar mass is less than one solar mass and its significance has also changed: it is now the largest mass that can collapse homologously, or as a unit. When the collapse is complete (*3*), the central part of the homologous core is converted into nuclear matter. The nuclear matter is compressed beyond its equilibrium density and then rebounds, launching a powerful shock wave. As the shock wave plows through the outer core, iron nuclei "evaporate" to form a gas of nucleons.

sure and so allows the implosion to accelerate further.

The first stage in the collapse of a supernova comes to an end when the density of the stellar core reaches a value of about 4×10^{11} grams per cubic centimeter. This is by no means the maximum density, since the core continues to contract, but it marks a crucial change in physical properties: at this density matter becomes opaque to neutrinos. The importance of this development was first pointed out by T. J. Mazurek of the Mission Research Laboratory in Santa Barbara, Calif., and by Katsushiko Sato of the University of Tokyo.

The neutrino is an aloof particle that seldom interacts with other forms of matter. Most of the neutrinos that strike the earth, for example, pass all the way through it without once colliding with another particle. When the density exceeds 400 billion grams per cubic centimeter, however, the particles of matter are packed so tightly that even a neutrino is likely to run into one. As a result neutrinos emitted in the collapsing core are effectively trapped there. The trapping is not permanent; after a neutrino has been scattered, absorbed and reemitted many times, it must eventually escape, but the process takes longer than the remaining stages of the collapse. The effective trapping of neutrinos means that no energy can get out of the core.

The process of electron capture in the early part of the collapse reduces not only the electron pressure but also the ratio of electrons to nucleons, the quantity that figures in the calculation of the Chandrasekhar mass. In a typical presupernova core the ratio is between .42 and .46; by the time of neutrino trapping it has fallen to .39. This lower ratio yields a Chandrasekhar mass of .88 solar mass, appreciably less than the original value of between 1.2 and 1.5.

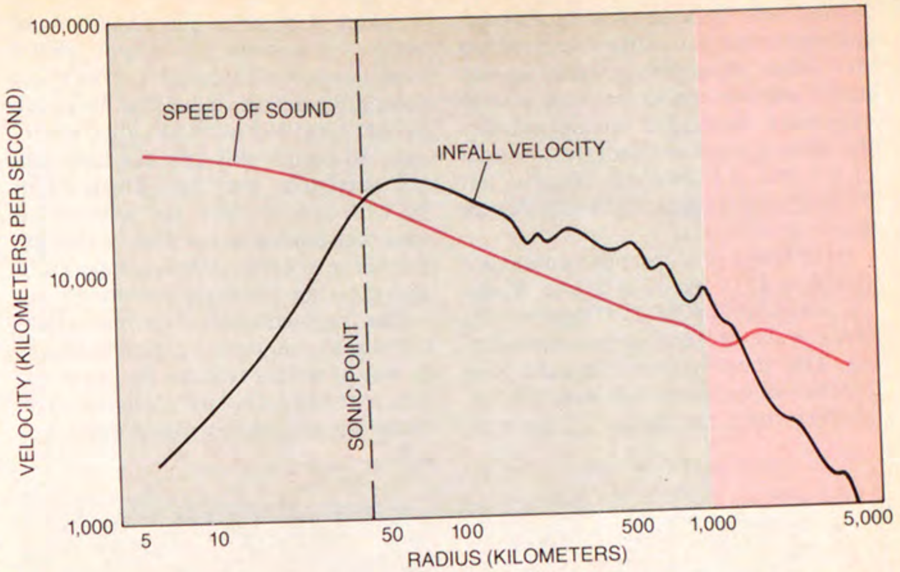
At this point the role of the Chandrasekhar mass in the analysis of the supernova also changes. At the outset it was the largest mass that could be supported by electron pressure; it now becomes the largest mass that can collapse as a unit. Areas within this part of the core can communicate with one another by means of sound waves and pressure waves, so that any variations in density are immediately evened out. As a result the inner part of the core collapses homologously, or all in one piece, preserving its shape.

The theory of homologous collapse was worked out by Peter Goldreich and Steven Weber of Caltech and was further developed by Amos Yahil and James M. Lattimer of the State University of New York at Stony Brook. The shock wave that blows off the outer layers of the star forms at the edge of the homologous core. Before we can give an account of that process, however, we must continue to trace the sequence of events within the core itself.

Chandrasekhar's work showed that electron pressure cannot save the core of a large star from collapse. The only other hope for stopping the contraction is the resistance of nucleons to compression. In the presupernova core nucleon pressure is a negligible fraction of electron pressure. Even at a density of 4×10^{11} grams per cubic centimeter, where neutrino trapping begins, nucleon pressure is insignificant. The reason is the low entropy of the system. At any given temperature, pressure is proportional to the number of particles per unit volume, regardless of the size of the individual particles. An iron nucleus, with 56 nucleons, makes the same contribution to the pressure as an isolated proton does. If the nuclei in the core were broken up, their pressure might be enough to stop the contraction. The fissioning of the nuclei is not possible, however, because the entropy of the core is too low. A supernova core made up of independently moving protons and neutrons would have an entropy per nucleon of between 5 and 8, whereas the actual entropy is less than 1.

The situation does not change, and the collapse is not impeded, until the density in the central part of the core reaches about 2.7×10^{14} grams per cubic centimeter. This is the density of matter inside a large atomic nucleus, and in effect the nucleons in the core merge to form a single gigantic nucleus. A teaspoonful of such matter has about the same mass as all the buildings in Manhattan combined.

Nuclear matter is highly incompressible. Hence once the central part of the core reaches nuclear density there is powerful resistance to further compression. That resistance is the primary source of the shock waves that turn a stellar collapse into a spectacular explosion.



SONIC POINT marks the boundary of the homologous core. It is the radius at which the speed of sound is equal to the velocity of the infalling material. A sound wave at the sonic point moves outward at the speed of sound in relation to the material it is passing through, but since that material is falling inward at the same speed, the wave stands still in relation to the center of the star. As a result a disturbance inside the core cannot reach the outside. The graph is based on calculations done by W. David Arnett of the University of Chicago.

Within the homologously collapsing part of the core, the velocity of the infalling material is directly proportional to distance from the center. (It is just this property that makes the collapse homologous.) Density, on the other hand, decreases with distance from the center, and as a result so does the speed of sound. The radius at which the speed of sound is equal to the infall velocity is called the sonic point, and it marks the boundary of the homologous core. A disturbance inside the core can have no influence beyond this radius. At the sonic point sound waves move outward at the speed of sound, as measured in the coordinate system of the infalling matter. This matter is moving inward at the same speed, however, and so the waves are at a standstill in relation to the center of the star.

When the center of the core reaches nuclear density, it is brought to rest with a jolt. This gives rise to sound waves that propagate back through the medium of the core, rather like the vibrations in the handle of a hammer when it strikes an anvil. The waves slow as they move out through the homologous core, both because the local speed of sound declines and because they are moving upstream against a flow that gets steadily faster. At the sonic point they stop entirely. Meanwhile additional material is falling onto the hard sphere of nuclear matter in the center, generating more waves. For a fraction of a millisecond the waves collect at the sonic point, building up pressure there. The bump in pressure slows the material falling through the sonic point, creating a discontinuity in velocity. Such a discontinuous change in velocity constitutes a shock wave.

At the surface of the hard sphere in the heart of the star infalling material stops suddenly but not instantaneously. The compressibility of nuclear matter is low but not zero, and so momentum carries the collapse beyond the point of equilibrium, compressing the central core to a density even higher than that of an atomic nucleus. We call this point the instant of "maximum scrunch." Most computer simulations suggest the highest density attained is some 50 percent greater than the equilibrium density of a nucleus. After the maximum scrunch the sphere of nuclear matter bounces back, like a rubber ball that has been compressed. The bounce sets off still more sound waves, which join the growing shock wave at the sonic point.

A shock wave differs from a sound wave in two respects. First, a sound wave causes no permanent change in its medium; when the wave has passed, the material is restored to its former state. The passage of a shock wave can induce large changes in density, pressure and entropy. Second, a sound wave—by definition—moves at the speed of sound. A shock wave moves faster, at a speed determined by the energy of the wave. Hence once the pressure discontinuity at the sonic point has built up into a shock wave, it is no longer pinned in place by the infalling matter. The wave can continue outward, into the overlying strata of the star. According to computer simulations, it does so with great speed, between 30,000 and 50,000 kilometers per second.

Up to this point in the progress of the supernova essentially all calculations are in agreement. What happens next, however, is not yet firmly established. In the simplest scenario, which we have favored, the shock wave rushes outward, reaching the surface of the iron core in a fraction of a second and then continuing through the successive onionlike layers of the star. After some days it works its way to the surface and erupts as a violent explosion. Beyond a certain radius—the bifurcation point—all the material of the star is blown off. What is left inside the bifurcation radius condenses into a neutron star.

Alas! Using presupernova cores simulated in 1974 by Weaver and Woosley, calculations of the fate of the shock wave are not so accommodating. The shock travels outward to a distance of between 100 and 200 kilometers from the center of the star, but then it becomes stalled, staying at roughly the same position as matter continues to fall through it. The main reason for the stalling is that the shock breaks up nuclei into individual nucleons. Although this process increases the number of particles, which might be expected to raise the pressure, it also consumes a great deal of energy; the net result is that both temperature and pressure are sharply reduced.

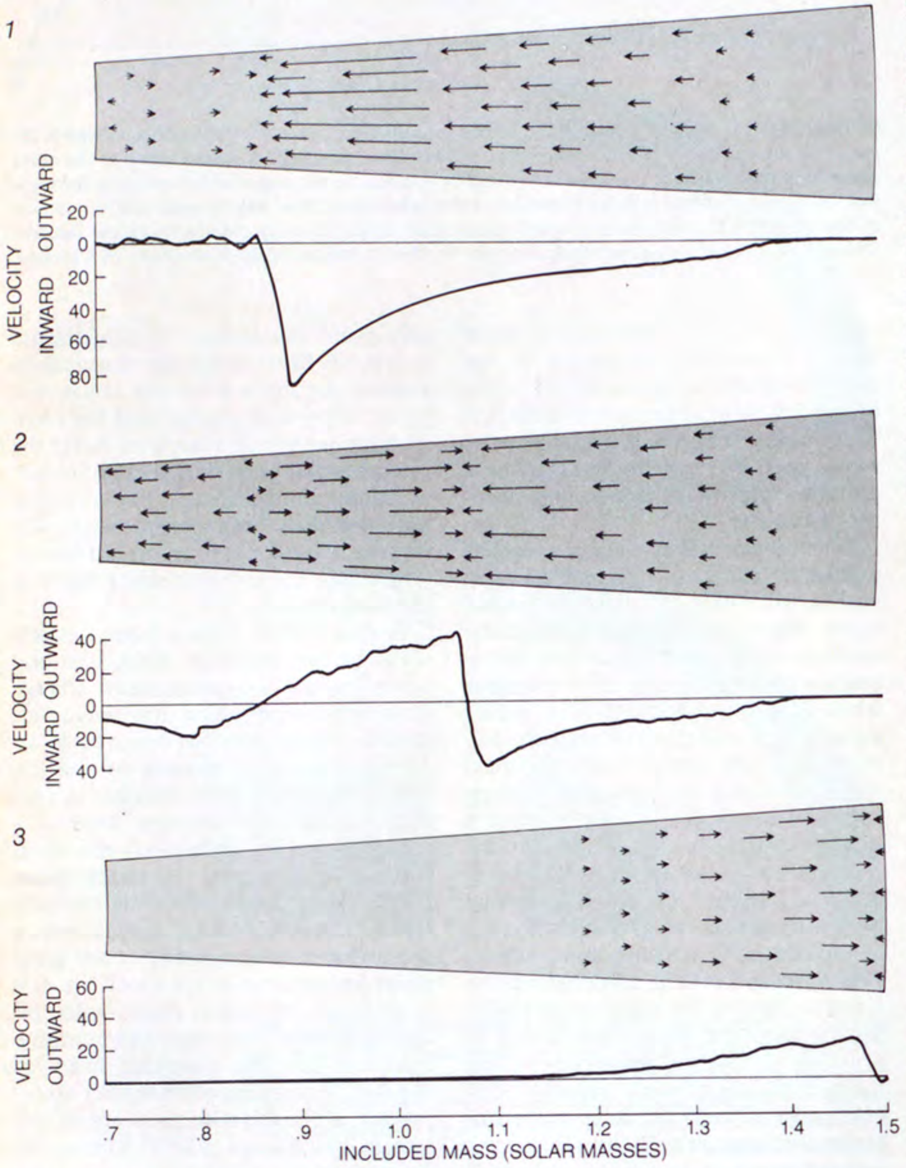
The fragmentation of the nuclei contributes to energy dissipation in another way as well: it releases free protons, which readily capture electrons. The neutrinos emitted in this process can escape, removing their energy from the star. The escape is possible because the shock has entered material whose density is below the critical value for neutrino trapping. The neutrinos that had been trapped behind the shock also stream out, carrying away still more energy. Because of the many hazards to the shock wave in the region between 100 and 200 kilometers, we have named this region of the star the "minefield."

It would be satisfying to report that we have found a single mechanism capable of explaining for all Type II supernovas how the shock wave makes its way through the minefield. We cannot do so. What we have to offer instead is a set of possible explanations, each of which seems to work for stars in a particular range of masses.

The place to begin is with stars of between 12 and about 18 solar masses. Weaver and Woosley's most recent models of presupernova cores for such stars differ somewhat from those they calculated a decade ago; the most important difference is that the iron core is smaller than earlier estimates indicated—about 1.35 solar masses. The homologous core, at whose surface the shock wave forms, includes .8 solar mass of this material, leaving .55 solar mass of iron outside the sonic point. Since the breaking up of iron nuclei has the highest energy cost, reducing the quantity of iron makes it easier for the shock to break out of the core.

Jerry Cooperstein and Edward A. Baron of Stony Brook have been able to simulate successful supernova explosions in computer calculations that begin with Weaver and Woosley's model cores. The main requirement, first surmised by Sidney H. Kahana of the Brookhaven National Laboratory, is that the homologous core be very strongly compressed, so that it can rebound vigorously and create an intense shock. Two factors cooperate to achieve this result in the simulations. The first factor is the use of general relativity rather than the force field of Newtonian gravitation. The second is the assumption that nuclear matter is much more compressible than had been thought.

Baron's first result showed that a star of 12 solar masses would explode if the compressibility of nuclear matter is 1.5 times the standard value. This seemed rather arbitrary, but then one of us (Brown) examined the problem with a sophisticated method of nuclear-matter theory. It turned out that the most consistent interpretation of the experimental findings yields a compressibility of 2.5 times the standard value! We then found that in 1982 Andrew D. Jackson, E. Krotscheck, D. E. Meltzer and R. A. Smith had reached the same conclusion by another method, but no one had recognized the relevance of their work to the supernova problem. We consider the higher estimate of nuclear compressibility quite reliable.



SHOCK WAVE can move faster than sound and so it can carry the energy and momentum of the rebound past the sonic point. Just before the bounce (*1*) the inner core has reached the density of nuclear matter and has stopped contracting, but overlying matter is about to fall onto the core at speeds of up to 90,000 kilometers per second. Two milliseconds later (*2*) the core is being driven further inward, but at the same time much of the infalling matter has rebounded to form a shock wave. After 20 milliseconds (*3*) the shock has reached the edge of the core. This mechanism of supernova explosion, in which the shock succeeds directly in bursting through the core, seems to work for stars of between 12 and 18 solar masses. Velocity profiles shown were calculated by Jerry Cooperstein of the State University of New York at Stony Brook. Velocities are given in thousands of kilometers per second.

The mechanism described by Baron, Cooperstein and Kahana seems to work for stars of up to about 18 solar masses. With still larger stars, however, even the powerful shock wave created in their simulations becomes stalled in the minefield. A star of 25 solar masses has about two solar masses of iron in its core, and so the shock wave must penetrate 1.2 solar masses of iron rather than .55 solar mass. The shock does not have enough energy to dissociate this much iron.

A plausible explanation of what might happen in these massive stars has recently emerged from the work of James R. Wilson of Lawrence Livermore, who has done extensive numerical simulations of supernova explosions. For some time it had seemed that when the shock wave failed, all the mass of the star might fall back into the core, which would evolve into a black hole. That fate is still a possible one, but Wilson noted a new phenomenon when he continued some of his simulations for a longer period.

In the collapsing stellar core it takes only 10 milliseconds or so for the shock wave to reach the minefield and stall. A simulation of the same events, even with the fastest computers, takes at least an hour. Wilson allowed his calculations to run roughly 100 times longer, to simulate a full second of time in the supernova. In almost all cases he found that the shock wave eventually revived.

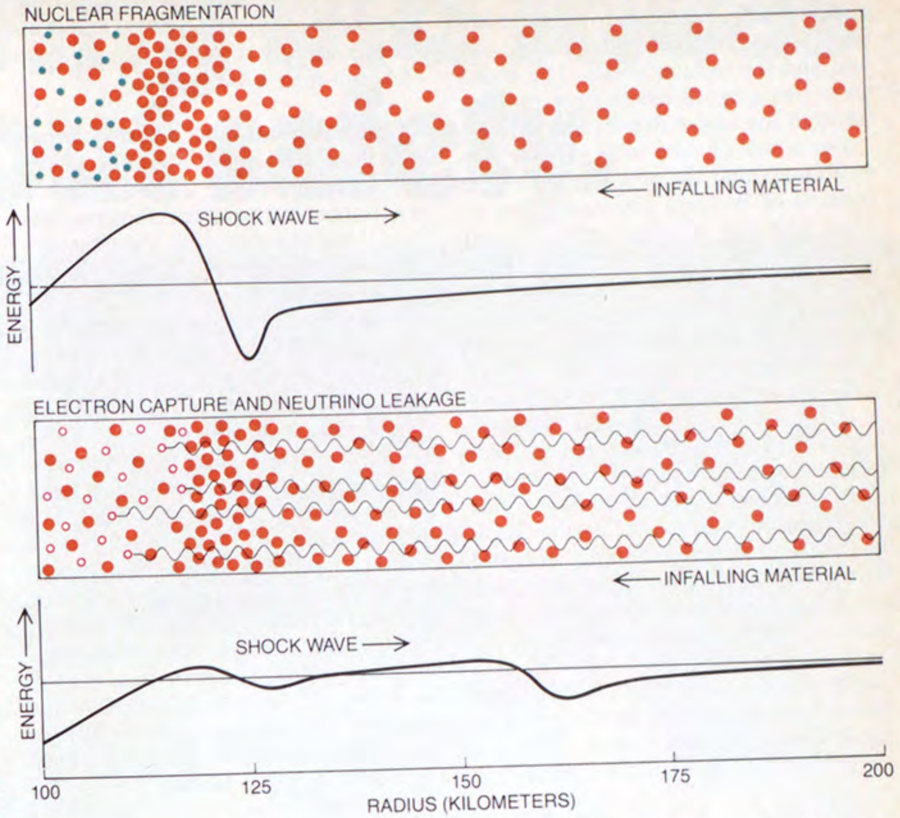
The revival is due to heating by neutrinos. The inner core is a copious emitter of neutrinos because of continuing electron capture as the matter is compressed to nuclear density. Adam S. Burrows and Lattimer of Stony Brook and Mazurek have shown that half of the electrons in the homologous core are captured within about half a second, and the emitted neutrinos carry off about half of the gravitational energy set free by the collapse, some 10^{53} ergs. Deep within the core the neutrinos make frequent collisions with other particles; indeed, we noted above that they are trapped, in the sense that they cannot escape within the time needed for the homologous collapse. Eventually, though, the neutrinos do percolate upward and reach strata of lower density, where they can move freely.

At the radius where the shock wave stalls only one neutrino out of every 1,000 is likely to collide with a particle of matter, but these collisions nonetheless impart a significant amount of energy. Most of the energy goes into the dissociation of nuclei into nucleons, the very process that caused the shock to stall in the first place. Now, however, the neutrino energy heats the material and therefore raises the pressure sharply. We have named this period, when the shock wave stalls but is then revived by neutrino heating, "the pause that refreshes."

Neutrino heating is most effective at a radius of about 150 kilometers, where the probability of neutrino absorption is not too low and yet the temperature is not so high that the matter there is itself a significant emitter of neutrinos. The pressure increase at this radius is great enough, after about half a second, to stop the fall of the overlying matter and begin pushing it outward. Hence 150 kilometers becomes the bifurcation radius. All the matter within this boundary ultimately falls into the core; the matter outside, 20 solar masses or more, is expelled.

The one group of stars left to be considered are those of from eight to 11 solar masses, the smallest stars capable of supporting a Type II supernova explosion. In 1980 Weaver and Woosley suggested that the stars in this group might form a separate class, in which the supernova mechanism is quite different from the mechanism in heavier stars.

According to calculations done by Nomoto and by Weaver and Woosley, in the presupernova evolution of these lighter stars the core does not reach the temperature needed to form iron; instead fusion ends with a mixture of elements between oxygen and silicon. Energy production then stops, and since the mass of the core is greater than the Chandrasekhar limit, the core collapses. The shock wave generated by the collapse may be helped to propagate by two circumstances. First, breaking up oxygen or silicon nuclei robs the shock of less energy than the dissociation of iron nuclei would. Second, far-



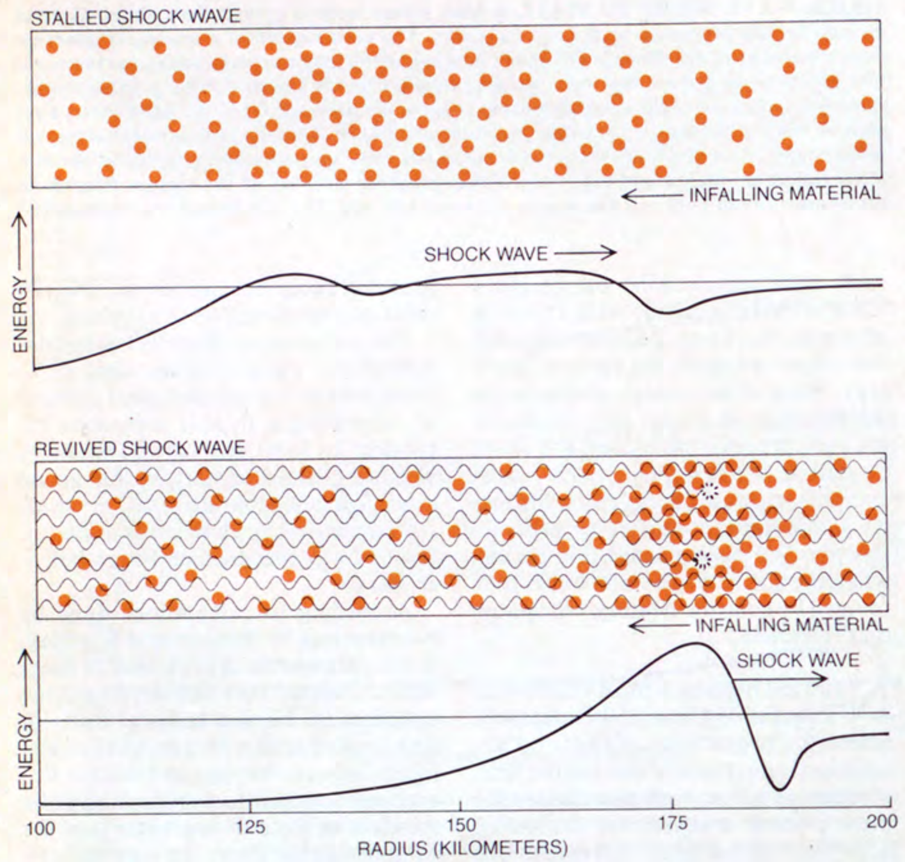
SHOCK WAVE SEEMS TO STALL in stars whose mass is greater than about 18 solar masses. Several processes sap the wave's energy. The most important is nuclear fragmentation: the energy of the shock is dissipated in breaking up iron nuclei, lowering the temperature and pressure behind the wave. Protons released by the fragmentation provide opportunities for electron capture, which further reduces the pressure. Once the wave enters a region of density less than 10^{11} grams per cubic centimeter, leakage of neutrinos carries off more energy. As a result of these effects the shock wave may slow to the speed of the material falling through it and make no further progress. Because of the various hazards to the shock, the authors call the region between 100 and 200 kilometers the "minefield."

ther out in the star the density falls off abruptly (by a factor of roughly 10 billion) at the boundary between the carbon and the helium shells. The shock wave has a much easier time pushing through the lower-density material.

For a star of nine solar masses Nomoto finds that the presupernova core consists of oxygen, neon and magnesium and has a mass of 1.35 solar masses. Nomoto and Wolfgang Hillebrandt of the Max-Planck Institute for Physics and Astrophysics in Munich have gone on to investigate the further development of this core. They find that the explosion proceeds easily through the core, aided by the burning of oxygen nuclei, and that a rather large amount of energy is released.

Two recent attempts to reproduce the Nomoto-Hillebrandt results have been unsuccessful, and so the status of their model remains unclear. We think the greater compressibility of nuclear matter assumed in the Baron-Cooperstein-Kahana program should be helpful here. Of course it is possible that stars this small do not give rise to supernovas; on the other hand, there are suggestive arguments (based on measurements of the abundance of various nuclear species) that the Crab Nebula was created by the explosion of a star of about nine solar masses.

After the outer layers of a star have been blown off, the fate of the core remains to be decided. Just as gravitation overwhelms electron pressure if the mass exceeds the Chandrasekhar limit, so even nuclear matter cannot resist compression if the gravitational field is strong enough. For a cold neutron star—one that has no source of supporting pressure other than the repulsion of nucleons—the limiting mass is thought to be about 1.8 solar masses. The compact remnant formed by the explosion of lighter stars is well below this limit, and so those supernovas presumably leave behind a stable neutron star. For the larger stars the question is in doubt. In Wilson's calculations any star of more than about 20 solar masses leaves a compact remnant of more than two solar masses. It would appear that the remnant will become a black hole, a region of space where matter has been crushed to infinite density.



REVIVAL OF THE STALLED SHOCK WAVE in heavy stars may be due to heating by neutrinos. Their source is the collapsed core, which radiates the energy equivalent of 10 percent of its mass in the form of neutrinos. Only a small fraction of them are absorbed, but the flux is so intense that many iron nuclei are dissociated. Earlier in the evolution of the supernova the breakup of iron nuclei took energy from the shock wave, but since the process is now powered by external neutrinos, the dissociation no longer decreases shock energy.

Even if the compact remnant ultimately degenerates into a black hole, it begins as a hot neutron star. The central temperature immediately after the explosion is roughly 100 billion degrees Kelvin, which generates enough thermal pressure to support the star even if it is larger than 1.8 solar masses. The hot nuclear matter cools by the emission of neutrinos. The energy they carry off is more than 100 times the energy emitted in the explosion itself: some 3×10^{53} ergs. It is the energy equivalent of 10 percent of the mass of the neutron star.

The detection of neutrinos from a supernova explosion and from the subsequent cooling of the neutron star is one possible way we might get a better grasp of what goes on in these spectacular events. The neutrinos originate in the core of the star and pass almost unhindered through the outer layers, and so they carry evidence of conditions deep inside. Electromagnetic radiation, on the other hand, diffuses slowly through the shells of matter and reveals only what is happening at the surface. Neutrino detectors have recently been set up in mines and tunnels, where they are screened from the background of cosmic rays.

Another observational check on the validity of supernova models is the relative abundances of the chemical elements in the universe. Supernovas are probably the main source of all the elements heavier than carbon, and so the spectrum of elements released in simulated explosions ought to match the observed abundance ratios. Many attempts to reproduce the abundance ratios have failed, but earlier this year Weaver and Woosley completed calculations whose agreement with observation is surprisingly good. They began with Wilson's model for the explosion of a star of 25 solar masses. For almost all the elements and isotopes between carbon and iron their abundance ratios closely match the measured ones.

In recent years the study of supernovas has benefited from a close interaction between analytic theory and computer simulation. The first speculations about supernova mechanisms were put forward decades ago, but they could not be worked out in detail until the computers needed for numerical simulation became available. The results of the computations, on the other hand, cannot be understood except in the context of an analytic model. By continuing this collaboration we should be able to progress from a general grasp of principles and mechanisms to the detailed prediction of astronomical observations.