

SUPERNOVAE

By what mechanism do massive stars explode?
Neutrinos produced in the core and absorbed
in the outer layers play the most important role.

Hans A. Bethe

Supernovae are spectacular events. The recent one, SN1987A, emitted light at a rate 100 million times that of the Sun—and it was one of the fainter supernovae. Unfortunately, supernovae are very rare. The last one seen in our galaxy was Kepler's in 1604.

In the 1930s, Fritz Zwicky and Walter Baade set out to observe supernovae in other galaxies, and found many. They classified them into several types by spectrum and "light curve" (light intensity as a function of time). Now these have been combined into just two types: Type I are (mostly) white dwarf stars that receive large amounts of extra mass from a neighboring star. Type II are massive stars at the end of their evolution; they are the focus of this article.

Zwicky and Baade proposed that supernovae derive their energy from the gravitational collapse of the central core of a star. We now believe this applies only to type II supernovae, but for this type it is the generally accepted theory. They proposed that the core, of approximately the mass of the Sun, collapses into a neutron star and thereby liberates enormous amounts of gravitational energy—several times 10^{53} ergs—much more than the energy of the emitted light, which is of order 10^{49} ergs.

In the 1960s, when computers became available, Stirling Colgate and his collaborators worked on the mechanism of supernova explosions. They found two possibilities: The collapse of the core leads to a rebound that drives the outer parts of the star out with great force, or neutrinos emitted by the core are absorbed by material at intermediate distances, heat this material and expel it. It is now believed that both mechanisms, in succession, are important.

Collapse

I believe we now understand the mechanism of type II supernovae, but a lot of computation still needs to be

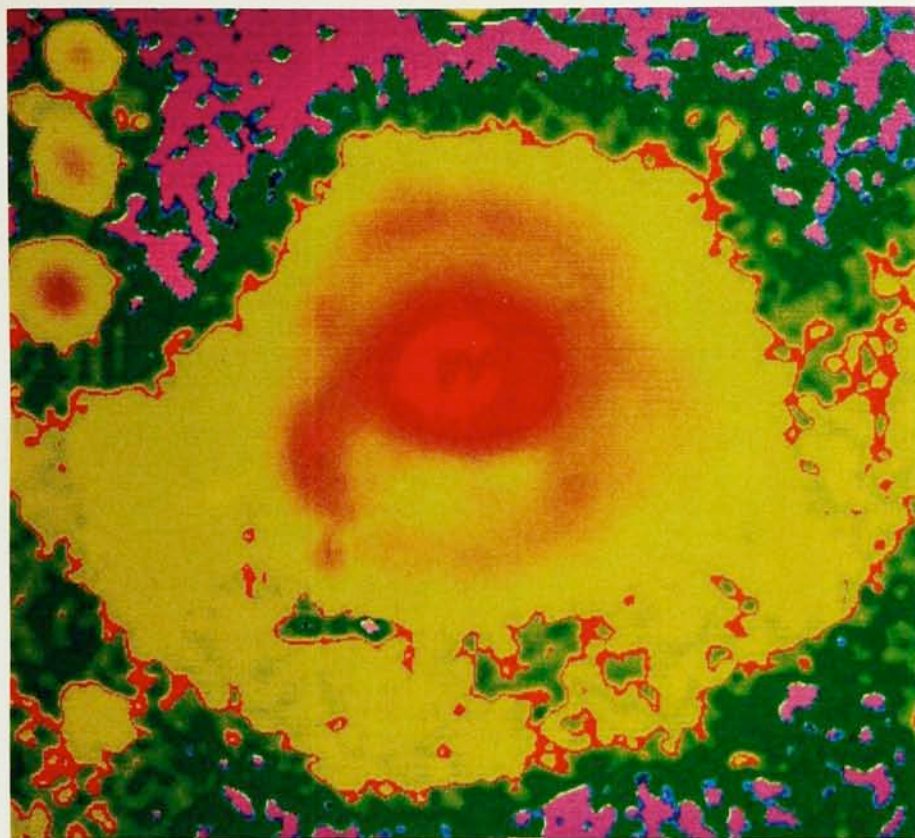
done to confirm this belief. Type II supernovae occur at the end of the evolution of massive stars, that is, stars of mass at least 8 times that of the Sun, $M_{\odot}$. Smaller stars suffer extensive mass losses from their surfaces while they are in their giant stage; they finally shrink and become white dwarfs. The progenitor of SN1987A was $18 M_{\odot}$.

Massive stars acquire an onion-like structure, with the hot central core surrounded by cooler outer layers. Nuclear reactions produce energy, first hydrogen reacting to become helium, then helium combining to form carbon, and so on. Near the end, the core consists of silicon and sulfur, and these react further to become iron. As is well known, Fe^{56} is the most strongly bound nucleus, so no further nuclear energy can be extracted. The core of iron grows, being held up for a while by the pressure of degenerate electrons. But there is a limit to this: When the core has grown to the so-called Chandrasekhar mass, electron pressure gets overwhelmed by gravity, and the core collapses. The exact value of the Chandrasekhar mass depends on the ratio Y_e of the number of electrons to the number of nucleons, and on the entropy. If the nuclear material consisted of C^{12} , O^{16} or Si^{28} , this ratio would be 0.50, but in Fe^{56} it is 0.464.

The pre-supernova evolution of massive stars has been carefully computed by Thomas Weaver of Lawrence Livermore National Laboratory and Stanford Woosley of the University of California, Santa Cruz, and independently by Ken'ichi Nomoto of the University of Tokyo, each with several collaborators. They agree that the mass of the iron core is about $1.4 M_{\odot}$, at least if the original (main sequence) mass of the star was $18\text{--}20 M_{\odot}$, as was the case with SN1987A. More massive stars have larger iron core masses. It is important that, beginning with the reaction between C^{12} nuclei, most of the energy produced is carried away by neutrinos rather than photons; as a consequence, the iron core has a rather low entropy, typically about 1 Boltzmann's constant k per nucleon.

There is general agreement among scientists about the gravitational collapse that starts the supernova

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Ancient nebula around Supernova 1987A. This computer-enhanced, false-color image of the innermost region around the supernova was processed to remove the point-like images of the supernova itself and its neighboring stars. The inner nebula (red oval) is composed of gas and dust. It and the more distant, fainter loops were formed by the supernova's progenitor star, a cool red supergiant, as that star shed its outer layers. The progenitor turned into a hot blue giant and then, after only a few thousand years, exploded as a supernova. The shell that the explosion blew away is still within the red oval. The field size is 13.5×12.6 arcseconds. (European Southern Observatory, New Technology Telescope image.)

process once the iron core exceeds the Chandrasekhar mass. The collapsing material remains similar to itself: If it has a certain density distribution at the beginning, it will have this same distribution later on, except that all the densities will have increased by the same factor. Each material element also keeps approximately its original (low) entropy. The collapse goes very fast, in less than a second. In this short time, a mass about equal to that of the Sun collapses from a radius of about 1000 km to one of perhaps 20 km, a process of a violence that is hard to imagine.

The nuclei capture some electrons and thereby become more neutron rich. But there is a limit to this: The neutrinos formed in the process are scattered by the nuclei, and at a density of about 10^{12} this scattering is strong enough to trap the neutrinos. Then the back reaction sets in, with neutrinos being captured by nuclei, giving electrons back. An equilibrium is reached at a certain electron fraction Y_e , which determines the resulting Chandrasekhar mass after collapse; that mass is about $0.7 M_\odot$ and the associated Y_e is about 0.36.

Shock wave

In the collapse, the density at the center increases steadily and finally reaches nuclear density. Nuclei melt together into nuclear matter, which is hard to compress further. Thus, pressure builds up, a pressure wave starts from the center of the star and finally turns into a shock wave. The pressure wave becomes a shock wave approximately when it encloses the Chandrasekhar mass of $0.7 M_\odot$. It is a very important fact that the shock starts only there, about halfway out to the surface of the iron core, and not at the center of the star.

In the second phase of the supernovae, the shock wave moves out from its starting sphere. For the past decade,

there has been a debate over whether this "prompt shock" manages to go all the way through the iron core and eject the outer part of the star. An East Coast group of theoretical astrophysicists, particularly Jerry Cooperstein of Brookhaven and Edward Baron of the State University of New York at Stony Brook, has tried very hard to show by computation that the prompt shock works. They were greatly helped by Gerald E. Brown of Stony Brook, who showed that nuclear matter may be considerably more compressible than had been believed. This boosts the magnitude of the prompt shock in the models because it permits the inner core to be compressed more in the collapse, especially if general relativity is used in the calculation. After this strong compression follows a strong rebound—a strong prompt shock.

A West Coast group at Lawrence Livermore National Laboratory, consisting of James R. Wilson, Richard L. Bowers and Ronald Mayle, computes that the prompt shock fails. The main reason is that the shock dissociates nuclei such as Fe into free nucleons, which costs about 9 MeV per nucleon, using up the shock's energy. There is not enough energy in the shock to dissociate all the material between $0.7 M_\odot$ and the surface of the iron core, at $1.3 M_\odot$. If the shock started at the center of the star, the energy deficit would be even worse. For some time it was hoped that the iron core might be smaller, perhaps $1.1 M_\odot$, but stellar evolution computations now appear to show rather definitely that it is $1.3 M_\odot$ or greater.

The situation is aggravated by the fact that the free protons and neutrons eagerly capture electrons (or positrons, which are plentiful in statistical equilibrium) and convert them into neutrinos or antineutrinos, which escape. With all this, it now seems definite that the prompt shock is not sufficient to explode the star. The shock does, however, move out to some distance—300 to

500 km—from the center. In this way, the prompt shock is essential as a preparation for the next stage.

The third stage of the supernovae mechanism was discovered in 1982 when Wilson accidentally left a computer operating overnight so that it covered a much longer time in the evolution of the shock than usual—more than half a second, in fact. He discovered that the shock got started again, and found that this was due to the absorption of neutrinos.

Neutrinos are emitted copiously by the core of the star, which will finally become a neutron star. But at this early time, in the first few seconds after collapse, the core is very hot, several times 10^{11} K. The only way it can cool down is by emitting neutrinos—electromagnetic radiation is hopelessly trapped in the material. It was these neutrinos that were observed in connection with supernova 1987A.

Reviving the shock

The neutrinos move out through the star and have some chance (on the order of a percent) of being captured at intermediate distances—on the order of 100 km from the center of the star. They heat the material there, and thus generate pressure and revive the shock. This is Wilson's theory.

This theory worked well in some computer runs but not in others. In the latter cases, Wilson's group found it necessary to increase the flux of neutrinos from the core, by an artifice. In addition, all computations (except one) gave too small a result for the energy of the supernova, 0.4×10^{51} erg, while the best value from supernova 1987A is about 1.5×10^{51} erg.

The reason is probably that the neutrino energy gets deposited at a moderate distance from the center, about

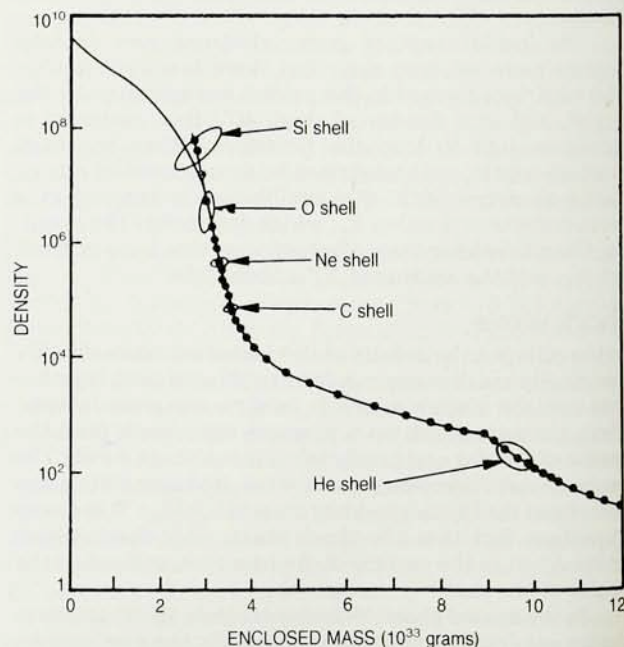
100 km, while the energy is needed at the shock front to drive it outward. This becomes increasingly difficult as the shock moves out—that is, as it is successful.

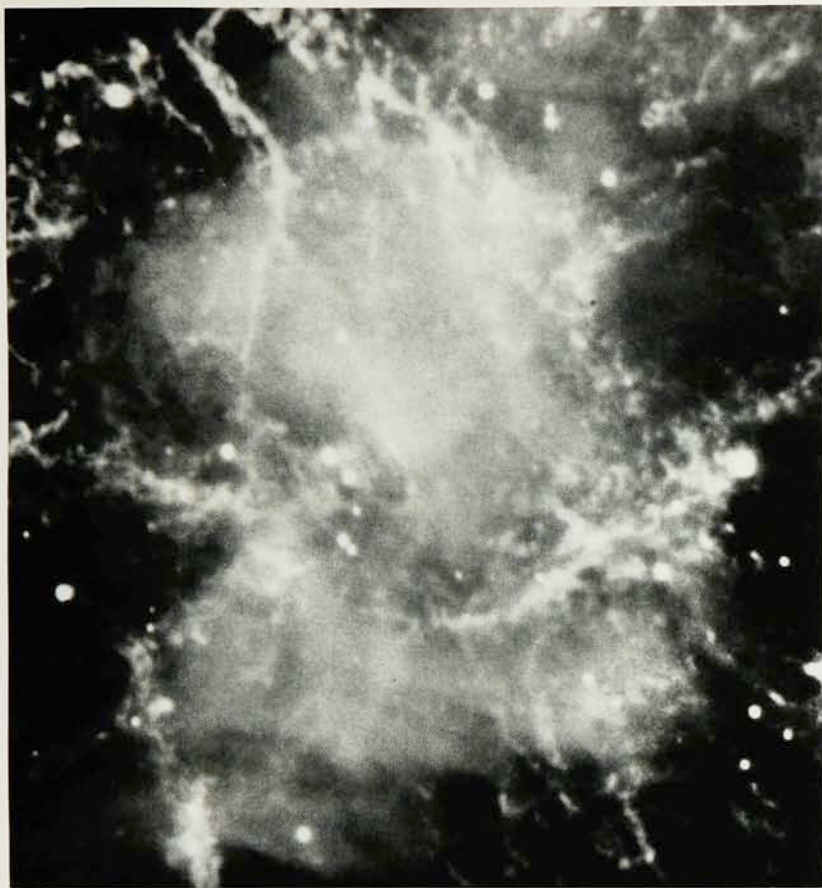
Maintaining the shock. The solution seems to lie in a fourth stage of supernova development: convection. Because neutrino energy is mostly absorbed at moderate distances from the star's center, it builds up high entropy there, while the entropy farther out remains lower. Such a negative gradient of entropy is the classic condition for convection, as Martin Schwarzschild recognized decades ago. Such convection is essential for understanding the structure of the Sun, and has been used successfully in the theory of stellar evolution.

There is a difference: Stellar evolution takes millions of years, so that a very small entropy gradient suffices to drive convection, while the supernova process takes fractions of a second, and therefore requires a large entropy gradient. But this gradient can be calculated using standard convection theory. Convection occurs normally in convection cells in which the material circulates, the hot material moving up on one side of the cell and the cooler material down on the other side; this phenomenon can actually be observed on the surface of the Sun. The velocity of circulation depends on the entropy gradient and can be a substantial fraction of the velocity of sound.

On this general principle, the energy deposited by neutrinos can be convected to the shock front and can keep the shock moving out. I have been able to estimate the energy in the shock and have found it to be about 1% of the energy flux in the neutrinos, and thus about 10^{51} erg, in agreement with the observed energy in supernova 1987A. I should mention, however, that this theory has not yet been accepted by the community of

Density distribution before supernova collapse.
(Based on W. D. Arnett, *Astrophys. J.* **218**,
815, 1977.)





Crab Nebula, the remnant of a star that exploded as a supernova in the year 1054. This view of the central area was obtained with a CCD camera through a red broad-band filter. (European Southern Observatory, New Technology Telescope image.)

scientists engaged in the supernova problem.

When the shock has progressed to about 3000 km, nuclear reactions take place in which the pre-existing elements—O, Si or S—are converted into Fe and intermediate elements. Because these reactions are extremely fast, taking place in about a second, Fe^{56} is not formed directly. What forms instead is Ni^{56} , the most tightly bound nucleus that consists entirely of alpha particles. This material, being in the ejecta, subsequently decays by positron emission into Co^{56} and then into Fe^{56} . The intermediate nucleus, Co^{56} , has a half-life of 77 days, and its decay supplies most of the light energy of SN1987A. The majority of type II supernovae, however, are powered at the maximum of light emission, and perhaps two months beyond, by the energy left by the shock in the hydrogen envelope, and only later by the radioactive decay of Co^{56} .

Once the shock has reached 3000 km, the influence of gravity becomes rather minor, and the shock progresses automatically through the rest of the star, bringing its internal energy with it. Once it breaks out of the star, light appears, first in the far ultraviolet, then (after about a day) shifting to the visible. Initial temperatures, as deduced from the spectra, are well above 100 000 K, but soon decrease to about 5500 K, slightly cooler than the surface of the Sun. After a few months, most of the radiation is in the infrared.

Supernova 1987A, in the large Magellanic Cloud, has been observed in very great detail from observatories in Chile and South Africa. The observations have generally confirmed the theory and have given us a much firmer understanding of supernovae. They have been analyzed theoretically, especially by Woosley and by Nomoto, each

with several collaborators. Woosley and Weaver give a very good account in the August 1989 *Scientific American*.

It was very helpful in the analysis that neutrinos have been observed at Kamiokande in Japan and at Fairport in Ohio. The neutrinos give the precise time of the explosion—or rather, the time when radiation from the supernova arrived at Earth after transversing space with light velocity for about 160 000 years. Neutrinos, once they are emitted from the proto-neutron star, travel unimpeded through the rest of the star and through interstellar space. By contrast, electromagnetic radiation is closely coupled to the matter, and therefore can emerge only when the shock breaks out of the surface. By measuring the time from the neutrino signal to the first light, astrophysicists determined the time it took the shock to transverse the star, and have concluded that the progenitor was relatively small in diameter, in agreement with the fact that it was blue rather than red.

The energy can be determined most reliably from the supernova's expansion velocity, as measured by the Doppler effect, together with a (mostly theoretical) estimate of the masses involved. This gives the previously mentioned result of $(1.5 \pm 0.5) \times 10^{51}$ erg.

Through careful and extensive observation, and through intense theoretical analysis, we now, I believe, have a good general picture of the mechanism of type II supernovae. To confirm this picture and to obtain reliable numerical results will require a lot of computation. If this computation is successful, the way will be open to investigate how this phenomenon depends on the mass and other properties of the progenitor star, to determine how many nuclei of various types are created in the explosion and to refine other quantitative predictions. ■