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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 the 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 greater by factors of 10 to 100 times more than the electromagnetic energy-the energy carried away by the countless 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, uninteresting object. In some cases the mass 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, what makes it happen? And if it does happen, how is the process driven? The answer to that latter question is that the process is driven by the tendency of a dying star to collapse and the tendency of the material that collapses to bounce outward in a shock wave.

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 1930s by Fritz Zwicky of the California Institute of Technology. About half of the supernovas Zwicky studied exhibited a quite consistent pattern: the luminosity increased steadily for about three weeks and then declined gradually over a period of 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. 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 basic idea 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. M. Burbidge, Geoffrey R. Burbidge, and William A. Fowler, of Caltech, and Hoyle. They proposed that when a massive star reaches the end of its nuclear fuel, the outer layers of the star become cooler than the core, which is still hot. The outer layers then contract and bounce outward in a shock wave, expelling the rest of the star's mass, including iron. At maximum speed, the outer layers of the star reach a speed of 30,000 kilometers per second or more. In the wake of the shock wave, 800 kilograms per second are expelled in the form of a shock wave. The shock wave is strong enough to break up the outer layers of the star, expelling them into space as a supernova.

Collapsing and rebounding are the initiating events in a supernova explosion. Here the core of a massive star, which is composed of iron, reaches its highest density. Each core 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.

The largest stars proceed all the way out, but the extreme compression of the collapse converts the iron core into a neutron star surrounded by a shell made up of various heavy elements, including iron. At maximum speed, the outer layers of the star reach a speed of 30,000 kilometers per second or more. In the wake of the shock wave, 800 kilograms per second are expelled in the form of a supernova.
way to the final, iron-core stage of the evolutionary sequence. The star's size of the sun gets no further than helium burning and the smaller stars stop with hydrogen fusion. A larger star also fuses hydrogen and helium, and then heavier elements, and the more massive it is, the 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 on the sun, the whole of the sun's fuel will take 10 billion years, a star 10 times as massive can consume its hydrogen fuel in 1,000 times faster. Regardless of how long it takes, all the usable fuel in a 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 white dwarf 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 30 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 potential 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 limit. 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, with its radius slowly decreasing until it becomes a black dwarf. How can this be? The key to the explanation is that the electrons can still escape and, if there are not too many of them, the electron pressure from the binary companion is attractive instead of repulsive. This attractive pressure is capable of giving the white dwarf enough mass to fall 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 star's explosive carbon burn- ing triggers Type I supernovas, as first noted by Hoyle and Fowler. More detailed models have since been devised by many astrophysicists, most notably 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 explosion is actually not explosively destructive. Instead the propogates like the burning of a fuse rather than like the explosion of a gunpowder charge. As a result the task of analysis also becomes harder at this point, so that theory relies on the assumption that this is a deflagration rather than a detonation.

Even if a star has been less violent than a detonation, the white dwarf is completely disrupted. The initial binding energy that holds the star together is approximately $10^6$ ergs; the energy generated by the explosion is $10^20$ times greater ($2 \times 10^3$ ergs), enough to lift a mass of 10,000 kilograms per second per second of supernova remnant mass. This is why the explosion nucleation 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 as a function of time decays according to the radioactive decay is just right to account for the nickel's presence. Subsequent analysis reveals that the deposits of the brightness decline light emission from Type I supernovas.

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

In tracing the history of a Type II supernova, we start with the star at some moment when the fusion of silicon nuclei to form iron first becomes possible at a temperature and density at which the fusion of helium is not. This cycle then repeats, at a steadily increasing pace, through the burning of carbon, oxygen, and neon to the final stage of silicon and, finally, iron.

The sequence shown is for a massive star, where the fusion of carbon, oxygen, and nitrogen, and it has the onomolike structure described above.

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

With the final fusion reaction begins, a core made up of iron will not related elements to form at the center of the star, within a shell of sodium. Fusion continues at the center between the iron core and the silicon shell. The density and pressure are highest. Within the core, however, there is no longer any production. The core finally collapses when the iron core is an inert sphere under great pressure. It is thus in the same pressure and core mass as when a white dwarf 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 a large mass of 2.5 solar masses. We noted above that for a white dwarf the Chandrasekhar mass is equal to 1.4 solar masses; for the iron core of a large star the mass may be somewhat different, but it is probably in the range between 2.5 and 3.0 solar masses.

When the Chandrasekhar mass has been attained, the pace speeds up still more. The core that was built in a day collapses to a very small neutron star, less than a kilometer in diameter. The task of analysis also becomes harder at this point, so that theory relies on the assumption that this is a deflagration rather than a detonation.

The study of Type Ia supernovas has been made in a period of years by a number of workers, including W. David Arnett of the University of Chicago and a group at the Lawrence Livermore National Laboratory headed by Thomas A. Weidemann. These stars are 100,000 times brighter than the sun; even so, they are very faint compared to their brightness. They are the "burners" of stars: we and our civilization are based on the fusion of energy into the star core. 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 seems that the explosion of a white dwarf is as chaotic a process, but in fact it is quite orderly. Indeed, the overall collapse of the core is an order of magnitude greater, or lower, than that of the star. It is easy to see why. In a hydrogen fusion chain, each reaction raises the temperature of the next reaction. In a white dwarf, however, each reaction lowers the temperature of the next reaction. The net result is that the collapse accelerates.

It is worthwhile tracing in some detail the initial stages in the sequence. One of the first signs of the core compression raises the temperature of the core, which might be expected to cause the core to collapse initially. A substantial fraction of the energy released is captured by the core, initially the entropy of the core increases, expressed in units of Boltzmann's constant, is about $1.5 \times 10^{54}$ solar masses.
The neutrino is an alkali particle that is seldon integers with other forms of matter. Most of the neutrinos that strike the earth, for example, are on the way through it without once colliding. But, if the density exceeds 40,000 grams per cubic centimeter, however, the particles of matter are packed so tight 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, however, after a neutrino has been scattered, absorbed and remitted many times, it is eventually free; but the process takes longer than the remaining entropy is lost of the system. The effective trapping of neutrinos means that energy can get out of the core.

The process of electron capture in the early part of the collapse reduces only the electron pressure but has also the ratio of electrons to nucleons, the quantity of which is used in the calculation of the Chandrasekhar mass. In a typical supernova core the ratio of free electrons between 42 and 46; by the time of neutrino trapping it has fallen to 39. This leaves a core in a Chandrasekhar mass of .8 solar mass, appreciably less than the initial values of between 1.2 and 1.5.

At this point the role of the Chandrasekhar mass in the analysis of the supernova explosion can be stated. At the outset the largest mass that could be supported by electron pressure is now about 1.2 solar masses. When the density reaches 4 x 10^49 grams per cubic centimeter, matter becomes opaque to neutrinos, once these free scattered, the core in the center of the sun fully gaseous at this point.

Within the homologously collapsing core the energy of neutrinos is directly proportional to the distance from the center. It is just this property that makes the collapse homologous. Density, on the other hand, falls off as the square of the distance from the center, and as a result so does the speed of sound. While the speed of sound is equal to the infall velocity, the collapse is not a simple cylinder of the homologous core. A disturbance in the core can have no influence beyond this radius. At the sonic point the 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 a stop. 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 as they move outward through the homologous core, both because the local sound decays and because they are moving up against a fire that is 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 behind the primary source of the shock waves that turn a stellar collapse into a supernova explosion.

The energy of the shock wave is transferred to the stellar core in the form of kinetic energy. The shock wave thus becomes the source of the energy that is radiated from the supernova. The shock wave is not a perfect conductor of energy, however, because of the presence of the neutrino field. The energy of the shock wave is thus transferred to the stellar core in the form of thermal energy, which is radiated as light.

The energy of the shock wave is thus transferred to the stellar core in the form of thermal energy, which is radiated as light. The energy of the shock wave is thus transferred to the stellar core in the form of thermal energy, which is radiated as light. The energy of the shock wave is thus transferred to the stellar core in the form of thermal energy, which is radiated as light. The energy of the shock wave is thus transferred to the stellar core in the form of thermal energy, which is radiated as light. The energy of the shock wave is thus transferred to the stellar core in the form of thermal energy, which is radiated as light.
second and then continuing through the sun as countable layers of the star. After some days it works its way to the sun's 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.

Alastair using presupernova core simulations by Weaver and Woosley, calculations of the fate of the shock wave are not so optimistic. The shock travels outward at a distance of between 100 and 200 kilometers, coming from the center of the star, but then it becomes scattered, starting at roughly the same position as matter continues to fall through it. The main reason for the scattering 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 ready capture electrons. But even the neutrons emitted in this process can escape, removing their energy from the star. The escape is possible because the shock has raised the material to a location below the critical value for neutrino trapping. The neutrino that has been trapped behind the shock also streams out, carrying away still more energy. Because of the many hazards to the shock wave in the region between 500,000 and 1,000,000 kilometers, this region of the star is the "mishmash." It would be satisfying to report that there is a single mechanism capable of explaining for all Type II supernovae how the shock wave makes its way through the mishmash. 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 core is smaller than earlier estimates indicated—about 1.35 solar masses. The homeologous core, at whose surface the shock wave forms, includes a solar mass of iron just above the maximum solar mass of iron outside the zone. Some models have suggested that the highest energy cost, reducing the density, and the easiest core to emerge for the shock to break out of the core.

Jerry Cooperstein and Edward A. Brown at Brookhaven National Laboratory have been able to simulate successful supernova explosions for cores of the main core structure, first surmised by Sidney H. Kahana of the Institute for Nuclear Physics. It is found the core is about 0.3 times less massive than the critical nucleus.

The revival is due to heating by neutrino emission. This heating is necessary because of the creation of free protons, which then create an intense shock wave. Two factors cooperate to produce this result. The first factor is the use of general relativistic equations rather than the force field of Newtonian gravitation. The second is the assumption that nuclear matter is 100% compressible than had been thought.

Carraro's first result showed that a star of 12 solar masses would explode if the inner core has reached a density of 100,000 kilometers per second. Two millionths later, 10-11 seconds, has a radius of 150,000 kilometers and is not far from the core. The question of whether the collapse or explosion of a presupernova explosion, in which the shock travels directly into the core, and the second, and emitted the neutrinos carried away the energy set free by the collapse, and about 10 million ergs.

It is now thought that the neutrinos are emitted by complex collisions with other particles; indeed, we are about to see that they cannot escape within the core and the collapse. Eventually, though, the neutrinos do produce a collision of solar mass protons, where they can move freely.

1. 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 neutrino energy then heats the material and then raises the pressure sharply. We have named this process, when the shock wave stalls but is then revived by neutrino heating, the "catastrophic collapse."
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 progressing 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 supernovae; on the other hand, there are suggestive arguments (based on measure-

ments 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 nuclear—the limiting mass is thought to be about 1.3 solar masses. The compact remnant formed by the explosion of light stars is well below this limit, and so these supernovas presumably leave a stable neutron star. For the larger stars the question is 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.

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 x 10³⁰ 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 made 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 the principles and mechanisms to the detailed prediction of astronomical observations.

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