Stellar Collapse and Supernova Explosions

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Supernovae are among the most spectacular and important events known to astronomers. A violent release of energy at the centre of a star heats the stellar material, so that for several months the star outshines entire galaxies composed of billions of stars. The explosion also blows off the outer layers of the star thereby forming a cloud of expanding gas, a supernova remnant. In at least some cases, the central core of the star is not dispersed but rather compressed to nuclear densities, to form a neutron star which may be observed as a radio pulsar or compact X-ray source.

Modern observations of supernovae and supernova remnants in our Galaxy and in external galaxies with ground-based optical and radio telescopes and with satellite-borne X-ray and ultraviolet instruments, have elucidated much of the physics of the surface region of the exploding star and the surrounding gas. The Einstein Observatory satellite has been used to study the X-ray emission from many supernova remnants, and in Fig. 1 we show an X-ray picture of the debris from the supernova which exploded in the constellation Cassiopeia about 300 years ago. While the phenomena which occur deep in the stellar interior are hidden by the overlying matter and are inaccessible to direct astronomical observations (though some day they may be accessible with the advent of neutrino and gravitational wave astronomy), recent laboratory experiments, especially those probing the weak interactions, have shed light on the mechanisms by which the cores of stars can produce explosions.

Observed supernovae can be separated according to their spectral characteristics into two general groups: Type I and Type II. The former are thought to involve mass exchange between a pair of stars each of which is not much more massive than the sun, and the latter type are believed to be the death throes of stars which are about ten or more times more massive than the sun. Here we shall focus on the progress which has been made in the past few years in understanding the origin of the Type II supernovae.

Background

To set the stage, let us first review the history of a star which a mass in the range 10-25 $M_{\odot}$, where $M_{\odot}$ is the solar mass. As a cloud of gas contracts to form a star, it heats up and eventually becomes sufficiently hot at the centre to burn hydrogen to form helium. Subsequently, when the hydrogen at the centre is exhausted, the stellar core contracts again and heats up until helium can be burned. With further contraction and rise in temperature, processes involving heavier nuclei, which are inhibited by large Coulomb barriers, can take place. When the central temperature reaches $\sim 3 \times 10^9$K ($\sim$ 0.3 MeV) and the central density is $\sim 2 \times 10^8$ g cm^{-3}, silicon nuclei can be burned to form heavier nuclei such as iron and other elements with atomic numbers close to that of iron. The star then consists of a hot dense core of mass about 1.5 $M_{\odot}$, surrounded by shells of lighter elements at lower densities and temperatures.

Even though the core of the star can no longer generate energy by nuclear reactions (the iron-like nuclei have the largest binding energy per nucleon), it continues to radiate energy by neutrino emission. This energy loss is compensated by the core contracting to higher densities and hence greater gravitational binding energies. Because of the relatively high mass of the core, the contraction cannot be halted by the pressure of the electrons and the compression eventually continues to at least nuclear densities; a neutron star or a black hole is thereby formed.

In the formation of a neutron star the gravitational binding energy of the core increases by about 10^{53} erg. This should be compared with the electromagnetic and kinetic energy of a supernova explosion which is of the order of 10^{50-51} erg, and with the binding energy of the matter outside the central core of the pre-supernova star which is about 10^{48} erg. Only a very small fraction of the energy which is released during the gravitational collapse and creation of a neutron star core, is required to produce the mass motion and radiation of a supernova display. The remainder is emitted primarily in the form of neutrinos. The main problem in the study of these supernovae is how, in fact, even this small fraction of the available energy is transformed into kinetic energy and internal energy in the overlying stellar material.

Role of Neutrinos

The discovery of the mechanism by which supernovae explode has to a large part been hindered by inadequate knowledge of the physics which is relevant at the high temperatures and densities which occur at the centre of a star. Recent advances in neutrino physics and in the nuclear physics of hot dense matter have greatly improved this situation.

In the early stages of the collapse many neutrinos are created by electron capture on protons, and they play an important rôle in current models of supernovae. An important step in the development of current ideas was the realization that dense matter is relatively opaque to neutrinos. The im-

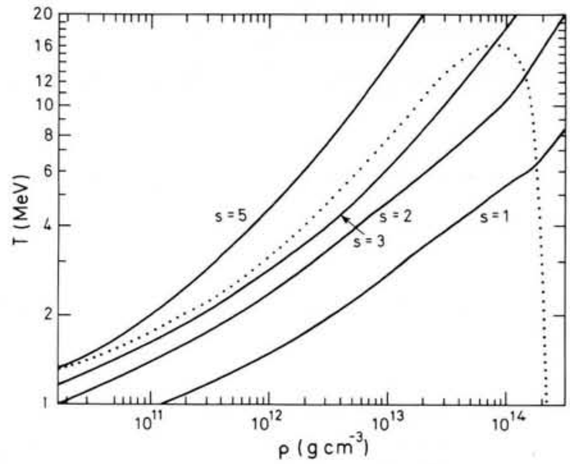
Fig. 1 - X-ray picture of the supernova remnant Cassiopeia A taken with the Einstein Observatory[1].

portant processes that limit the neutrino mean free path are ones involving the weak neutral current, which gives rise to scattering of neutrinos from nucleons, $\nu_e + n \rightarrow \nu_e + n$. These are much more important than the more familiar charged current processes which give rise to absorption of neutrinos on neutrons, $\nu_e + n \rightarrow e^- + p$, and scattering of neutrinos by electrons, $\nu_e + e^- \rightarrow \nu_e + e^-$. The importance of the neutral current processes is enhanced by coherent scattering. Scattering of a low-energy neutrino by a nucleon in a nucleus does not change the state of the nucleon, and therefore for a neutrino with a wavelength large compared with the size of the nucleus, the amplitudes for scattering from different nucleons in the same nucleus add coherently. The scattering amplitude is thus proportional to the mass number A. The cross section of a single nucleus is proportional to the square of the scattering amplitude, and therefore varies as A^2; consequently the cross section per nucleon in a nucleus is proportional to A. Since A is typically 60 or more, this leads to a substantial enhancement of the cross section over that for scattering from individual nucleons. This effect is completely analogous to the electromagnetic scattering of an electron from a nucleus where the amplitudes for scattering from individual protons add coherently, giving a total scattering amplitude proportional to Z, the total number of protons.

At the densities when collapse first becomes rapid ($\sim 5 \times 10^9$ g cm^{-3}) neutrinos can escape relatively freely. However by the time a density $\rho \geq 10^{12}$ g cm^{-3} is reached, the time for a neutrino to diffuse out of the stellar core is comparable with the characteristic dynamic time scale, $\rho/(d\rho/dt)$, which is then several milliseconds. As a consequence, neutrinos are trapped in the star and the number of leptons in the star remains essentially fixed for the duration of the collapse. Neutrinos build up in the core, and, being fermions, they form a degenerate Fermi gas. Further electron captures are inhibited because of the blocking of the final neutrino states.

This has two important effects. First, the fraction of protons remains high, typically about one quarter of the total number of nucleons. This number should be compared with the value $\sim$ 0.05 typical for neutron star matter at nuclear densities when neutrinos can escape freely. The high proton concentration encourages the persistence of nuclei, due to the attraction between a proton and a neutron being greater than that between two protons or two neutrons. Second, the entropy of the matter ceases to change. Electron captures and neutrino escape are the main mechanisms by which the entropy changes during the collapse, and as a consequence of neutrino trapping both these processes are strongly inhibited.

Fig. 2 - Adiabats for hot dense matter as a function of density and temperature for a lepton fraction Y_l = 0.35. The entropy, s, is in units of Boltzmann's constant per nucleon. In the region within the dotted line more than 10% of the nucleons are in nuclei. (From Ref. 4).



The equation of state following neutrino trapping is determined by the lepton fraction and the entropy, both of which are essentially conserved in the subsequent collapse. At the start of the collapse the matter has an entropy of about 1 per nucleon in units of Boltzmann's constant. This implies that the matter is very well ordered, a point stressed particularly in Ref. 2. To appreciate this, we note that this is roughly the entropy of a perfect non-relativistic Fermi gas at a temperature of one fifth of the Fermi temperature.

During the collapse, the entropy and the number of leptons per nucleon change due to the electron captures and neutrino losses, but these quantities are remarkably insensitive to variations in the physical and astrophysical assumptions, as a series of simplified calculations we have made indicate[3]). For a wide range of conditions one finds that the number of leptons per nucleon is $\sim$ 0.3 and the entropy per nucleon $s \sim 1$. The quantity probably least well known is the electron capture rate on nuclei, but even a change of a factor 10^4 in this leads to little change in the conditions after neutrino trapping. Since very little entropy is generated by the electron captures, the matter is still well ordered during the later stages of infall.

State of Nucleons

The equation of state of hot dense matter is important for determining how far the collapse proceeds. The rate at which the collapse accelerates is proportional to the difference between the gravitational forces pulling in, and the internal pressure of the matter. For the low entropies and relatively high proton fractions which are expected, most of the nucleons are initially in nuclei. The heavy nuclei contribute little to the pressure, compared with the much more abundant electrons which form a relativistic degenerate gas. The electron pressure varies as $\rho^{4/3}$, the same dependence on ρ as the inward "gravitational pressure". Since the gravitational pressure overwhelms the electron pressure during the initial stages of the infall, this imbalance continues and the collapse can never be halted as long as electrons provide most of the pressure. The collapse must continue until the nuclear pressure becomes important, which occurs when the nuclei fill nearly all of space, that is at densities of the order of nuclear matter density ($\sim 3 \times 10^{14}$ g cm^{-3}). Further increase in density requires compressing nuclear matter, and leads to a more rapid rise of pressure with density.

To illustrate the conditions under which there are significant numbers of nuclei, we show in Fig. 2 the results of the calculations of Ref. 4. In the region within the dotted line more than 10% of the nucleons are in nuclei, and in fact over most of the region more than 50% are in nuclei. At the high density boundary, nuclei fill all of space, and at still higher densities matter is uniform. As the temperature increases at lower densities, nuclei evaporate and the nucleons form a uniform nucleon vapour. Adiabats are also shown in the Figure, and from these we can see, that only for an entropy per nucleon greater than about three does evaporation occur.

As we explained earlier, the collapse trajectory following neutrino trapping is given well by an adiabat, with $s \sim 1$. This indeed lies in the region where the bulk of the nucleons are in nuclei so that the nucleons give only a small contribution to the pressure. Under the conditions we are considering here most of the entropy is in the free nucleons. However the temperature on adiabats rises much less steeply than it would for a perfect non-relativistic gas, $T \sim \rho^{2/3}$. This is due to the effect of nuclear excited states. As the density increases, the free nucleons tend to heat up, while the temperature of the nuclear excited states tends to remain constant. This leads to a transfer of heat from the free nucleons to nuclear excited states, which therefore act as a refrigerator cooling the free nucleons. The nuclear excited states also play an important rôle in giving a greater statistical weight to nuclei, thereby allowing them to be present at temperatures as high as $\sim$ 10 MeV ($\sim 10^{11}$ K) at densities approaching nuclear densities.

The survival of nuclei up to nuclear density, implies that the pressure at low densities is provided almost entirely by relativistic electrons. The collapse can therefore be halted only at densities greater than that of nuclear matter. As a consequence, the core falls far into the gravitational potential well, and therefore a great amount of energy is available for blowing off the outer parts of the star. At the moment all workers agree on these points, but there is no consensus when it comes to the question of whether or not this energy can be transmitted to the outer parts of the star.

Supernova Explosion Mechanisms

A number of possibilities for the origin of supernova in massive stars are presently being explored. In all the proposed mechanisms the ultimate source of energy for the explosion is the increase in the gravitational binding energy of the central core. During the collapse, this energy can be converted into three forms which are potentially useful for producing a supernova explosion.

(1) If the collapse is rapid, the matter gains kinetic energy due to the infall; velocities greater than 10% of the speed of light are typical, corresponding to energies of the order of 10^{52} erg.

(2) The internal energy of a collapsed core is at first much greater than it would be if the core were cool and in beta equilibrium. For instance, a 1 $M_\odot$ core which retains 0.3 leptons per nucleon has an excess energy of $\approx 5 \times 10^{52}$ erg.

(3) If the core initially is rotating, then in order to conserve angular momentum the rotational energy of the core increases as the core contracts. Most of the recent investigations generally exploit one of these three forms of energy.

The simplest and perhaps most promising model is that of a spherically symmetric *hydrodynamic explosion.* The important ingredient in this model is that the kinetic energy gained in the initial infall is so large that the central part of the core considerably overshoots the equilibrium density and then reverberates. The interaction of the rebounding central region of the core with the matter which is still falling in creates a shock wave. If this shock wave is able to propagate into the outer portions of the star it could be the cause of the supernova explosion. Fig. 3 shows some results for the collapse of a 15 $M_\odot$ star (Ref. 5). The lines show the trajectories of mass shells, and the number on each line gives the total mass (in units of $M_\odot$) interior to the shell. Initially the shells fall inwards, and about 0·26 s from the start of the calculation, the inner shells rebound violently. Subsequently at least 1.1 $M_\odot$ settles down to form what will presumably be a neutron star. In this particular calculation some of the outer shells are expanding at greater than the escape velocity, and would be expected to transmit energy to the outer parts of the star, thereby creating a supernova display.

Two possibilities invoke departures from spherical symmetry. In one interesting model the explosion is driven by a *lepton pressure instability,* which generates convective motions which release a large fraction of the stored internal energy of the central core and produce an explosion. Even though neutrinos are trapped in the centre of the stellar core, they escape from the lower density regions at larger radii, and this material attains a much smaller ratio of leptons to nucleons. The surrounding lepton-poor material is thus "heavier" than the lepton-rich material near the centre of the core, i.e., the interchange of material from these two regions would lower the total energy. Buoyancy instabilities of the Rayleigh-Taylor type can develop and may release vast amounts of energy in neutrinos and convective mass motion.

Another possibility that has been explored is that rotational kinetic energy is converted into outward motion to yield an explosion. The collapsing core is thought to be threaded by a magnetic field. If the angular velocity is a varying function of radius, then the magnetic stresses will rapidly damp these motions. In the process the magnetic field is stretched and amplified. It has been suggested that the resulting magnetic stresses could be large enough to produce an explosion.

The exploration of the origin of supernovae has proved to be a complex, yet exciting, challenge. It involves the study of neutrino interactions and nuclear physics in conditions which are bizarre by the standards of normal laboratory physics. The final solution of the problem will doubtless stimulate equally exciting developments in other areas of physics.

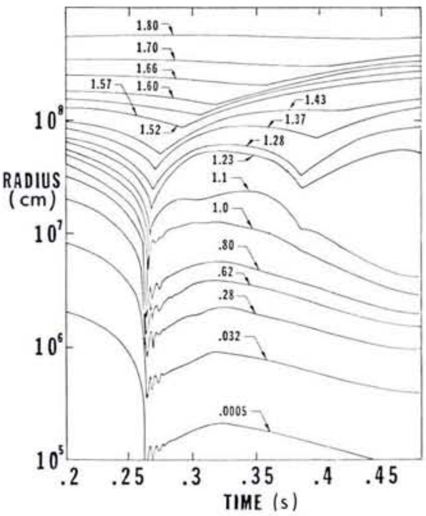


Fig. 3 - Radius versus time for selected mass shells in a collapsing 15 $M_\odot$ star. The numbers give the mass (in solar masses) interior to each shell. (Ref. 5).

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