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SUPERNOVA SHOCK

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Abstract

A violent shock is formed at the site of the collision of inner and outer cores of a collapsing star and the supernova explosion is born. Here we briefly review the evolution of the shock from its birth until its death.

Introduction

Supernovae are the extremely energetic outbursts, which are classified roughly into two types. Type I supernovae have regular light curves and are probably due to the sudden triggering of nuclear reactions in a white dwarf which has accreted external material Type II SN have variable light curves and are generally attributed to the collapse and subsequent explosion of highly evolved, very massive stars. The progenitor of SN 1987A which is of our interest is very likely *SK*-69 202 which was a typical B3 supergiant. The presence of hydrogen lines in its spectrum and the close resemble of its light curve with those SN II, show that SN 1987A is a Type II supernova and is the explosion of a massive star. Hence we shall only consider type II SN. The energy release is generally of the order of (1 2) x 10^{51} ergs, most of which is in kinetic energy of the expanding debris.

In an ordinary star, there are successive nuclear reactions involving H, He, C, O, Ne and Si. In the core of the star, all these reactions take place successively, the final one transforms Si into Fe at a temperature of about 5.10^9, so that $KT \simeq 0.5$ MeV. This reaction takes a few days; it starts at the center and works gradually outward. The core thereby becomes material of Fe, Ni and similar elements. When this core has grown to a Chandrasekhar mass of about 1.5 M_θ, gravitational collapse occurs. There are excellent reviews on the subject [Chevalier,1981; Bethe; 1984].

Start of the Shock

The collapsing core separates into two distinct regions. Material in the inner region collapses with a velocity proportional to its radius, which means this part of the core collapses as a single unit. The two regions collapse separately because no disturbance in the inner region can travel fast enough to reach and thereby influence the outer region. The maximum speed of collapse is about 7×10^4 kms/sec and it occurs near the boundary between the two regions.

The collapse continues until the inner core reaches the density of normal nuclear density, $\rho_0 = 2.7 \times 10^{14}$ gms/cm^3. Then the core material suddenly stiffens, which means that the infall velocity becomes very nearly zero, first at the center, and soon also at larger r. This sudden change of material velocity then generates a pressure wave which moves out with sound velocity. At this pressure wave the density will increase by a fraction $\frac{\Delta\rho}{\rho} = \frac{u}{a}$ where u is the velocity of the pressure wave and a is the sound velocity. Since the ratio $\frac{u}{a}$ is small near the center of the star and increases with r, there exists a mild pressure wave near the center which does not change the entropy. Therefore the core of the star remains essentially unshocked.

As the pressure wave proceeds to larger r, $\frac{u}{a}$ will increase. This leads to an increase in the entropy, which, according to the shcok theory is:

$$\Delta S = \frac{1}{12} \gamma(\gamma+1) \left(\frac{u}{a}\right)^3 \quad (1)$$

The point, where $\frac{u}{a} = 1$ is called the sonic point. Beyond the sonic point, the pressure wave becomes a shock which has a substantial discontinuity in density, entropy and velocity, and also sound waves from the interior cannot move out beyond that point. The sonic point essentially marks the surface of the unshocked core. The entropy increases in the shock wave and reaches (6-10) units. At $S \gtrsim 2.7$, the equation of state shows that nuclei dissociate into nucleons.

This dissociation costs about 9 MeV energy per nucleon, but it clearly increases the pressure. The sudden increase in pressure makes the material in the shocked region reverse its direction of motion and drives it out of the star. The shock, therefore, is the basis of the supernova phenomenon. The infall compresses the core of the star beyond the equilibrium density. So, the core then bounces back and expells the outside material with high velocity. The energy for this expulsion comes, of course, from the gravitational energy set free in the collapse. The shock carries this energy out.

As the shock wave moves out through the star, the core of the star remains behind. Since the collapse began when the core became larger than the Chandrasekhar limit, the core becomes a neutron star.

The nineteen SN 1987 neutrons detected by the Kamiokande-II detector and IMB detector told astronomers a great deal about what happened at th heart of SN 1987A, but they do not tell the fate of the shock. The shock wave forms in the interior of the iron core, some $\frac{1}{8} M_\theta$ out from the star's center. This means the shock wave must fight through the still collapsing outer core before it can destroy the rest of the star. If the core bounce is strong enough and the total size of the iron core is small, the shock wave should break through the outer core in $(1-2) \times 10^{-4}$ sec. If those conditions are not met, however, current supernova theory predicts the shock wave will stall. At this point the shock wave must be reenergized or the supernova will die, but there is no generally accepted mechanism to accomplish this. The question of how the shock wave gets through the collapsing outer core is the most significant remaining problem in supernova physics. Supernova 1987A has not helped us to resolve this question.

Hydrodynamic features of Evolution

Let us consider that the entire energy of the shock is deposited on the envelope of the star of radius $\approx 5\times10^{13}$ cm and $\rho = 10^{-8}$ g cm^{-3}. Initially the diffusion time scale is much larger than the hydrodynamic time scale, the diffusion does not play a significant role in the energy transport through the envelope. Therefore the intial flow is adiabatic. If one assumes that the envelope is at constant density and the effects of the inner core mass are negligible, the flow can be described by the similarity solution for a blast wave (Sedov, 1959). One aspect ofthe blast wave flow is that the density is sharply peaked out at the shock wave. Combining with the Rankine-Hugionot conditions for post shock pressure, the lower limit to the radius of the envelope above which the radiation pressure dominates gas pressure is for SN 1987A, of which $M \approx 8\ M_{\odot}$, $E_* \approx 10^{51}$ ergs, $R \geq 6.4\times10^{8}$ cm; For the required conditions in the supernova envelope, the gas pressure is only about 0.1% of the radiation pressure. Therefore the flow is that of a $\gamma = \frac{4}{3}$ adiabatic gas.

For a shock wave in an optically thick region in which the radiation pressure is at least 4.45 times the gas pressure in the final post shock region, the shock wave can be radiated by photons, i.e., it is a radiation dominated shock. In such a situation, the photons move ahead of the high pressure region and accelerate electrons through the Compton interaction. The electrons then accelerate the ions through electrostatic forces and coulomb forces. Ion viscous forces do not play a role in mediating the shock. The shock wave that propagates through the supernova envelope is a radiation dominated shock.

One of the assumptions here has been that the deposition of energy inside the envelope can be treated as a point explosion. Actually there is a mantle of processed material that is present inside of the envelope. Initially, all of the supernova energy is deposited in the mantle and that material attains a high velocity. However, it is effectively decelerated by the envelope gas because the envelope contains about twice as much matter as the mantle.A reverse shock wave is driven back through the mantle material causing it to move back toward the center of the supernova. Its energy is transferred to the envelope, where the flow is approximately described by the blast wave solution. The inward flow of the mantle material is eventually reversed by radiation pressure and it ends up moving outward at several hundred km/s. Falk et al. 1977, suggested that as the mantle gas expands and cools, it is possible that grain formation occurs.

As the shock wave *approaches* the stellar surface, the diffusion of radiation does become significant. The distance over which diffusion occurs is given by

$$l = \frac{\lambda c}{3V} \qquad (2)$$

where λ is the photon mean free path and V is the shock velocity. When the radiation can diffuse to an optical depth $\tau \approx 1$, the radiation begins to escape from the star. This occurs at an optical depth

$$\tau_l = l/\lambda = \frac{c}{3V} = 20\left(\frac{V}{5000\ \mathrm{km/s}}\right)^{-1} \qquad (3)$$

Approximately 90 minutes after the core of Sanduleak -69°202 collapsed the shock wave reached the surface of the star for SN 1987A. Until this time no electromagnetic radiation from the explosion had reached the outside world. The neutrinos offered the only evidence that the star had become a supernova. The escape of radiation decreases the radiation pressure support for the outer layers and they collapse to form a dense shell which is supported by gas pressure. The amount of mass involved in the shell is

$$\Delta M = 4\pi R^2 \Delta R \rho = 4\pi R^2 \, \tau_i / k \qquad (4)$$

which is less than 0.1% of the total ejected mass. The shell is subjected to Rayleigh-Taylor instability and smeared out.

Once the radiation does begin to stream away from the star, a radiation dominated shock wave can no longer be maintained. Radiation cannot accelerate the outer layers of the star to the velocities which have been attained by the deeper shocked layers of the star. As a result, viscous heating of the ions becomes important and a viscous shock forms. The transition is occurred at an optical depth of about unity.

A postshock gas had velocity of 7000 km/s yielding a shock velocity of 3500 kms^{-1}. The postshock gas temperature is expected to be

$$T = \frac{3}{16} \frac{\mu}{k} V_{sh}^2 \approx 2 \times 10^8 \, K \qquad (5)$$

where μ - mean particle weight and $V_{sh} \approx 10{,}000 \ \mathrm{kms}^{-1}$.
At $T_\gamma \approx 10^5$ K, viscous shock first begins to form. In the dense layers where the viscous shock first forms, the bremsstrahlung losses are somewhat larger than the compton losses. The compton losses become more important as the shock wave moves into lower density layer. While radiative cooling is important, the optically thin gas is shocked to a high temperature, then it cools and is added onto the dense shell described above

Typical hydrodynamic timescale for the supernova envelope is given by

$$t_h = \frac{R}{V} = 10^5 \left(\frac{R}{5 \times 10^{14} \, \mathrm{cm}}\right) \left(\frac{V}{5000 \, \mathrm{km/s}}\right)^{-1} s \qquad (6)$$

The compton cooling time becomes equal to the hydrodynamic time when

$$T_\gamma = 14000 \left(\frac{t_h}{10^5\,s}\right)^{-1/4} K \qquad (7)$$

This is actually a lower limit to the temperature because as the supernova expands, the shock wave becomes separated from the supernova photosphere and the radiation field is diluted. The supernova reaches the temperature in about 10 days, which is an upper limit to the time within which cooling is important for the postshock gas. After this time the evolution of the newly shocked gas is basically adiabatic.

With planar geometry, the acceleration of an adiabatic shock can be approximately described by

$$V_{sh} \sim \rho_0^{-0.2} \qquad (8)$$

where ρ_0 - preshock density

Eventually the supernova shell expands into the circumstellar medium. The situation may be similar to a dense spherical piston propagating onto a uniform medium. In this case, a shock wave moves into the ambient medium at a velocity 1.1 times the piston velocity, so that the shock radius is 1.1 times the piston radius.

As the remnant of the supernova expands, it goes through several well-defined stages: (1) In the first stage, the ejected mass exceeds the swept-up ambient mass, so that to lowest order the ejecta undergo free expansion. The dynamics in this stage are affected by both the density distribution of the pre-supernova star and that of the ambient material. (2) After the blast wave expands to the point that the swept-up, shocked mass of gas exceeds the ejected mass, the SNR enters the second stage, the adiabatic (or Sedov-Taylor) stage, and the dynamics becomes simple. For a uniform, homogeneous ambient medium, the distributions of density, velocity and pressure in this stage depend only upon two-dimensional parameters, the energy of the explosion E_b and the ambient density ρ_0 . Even if the initial Explosion is aspherical, it approaches sphericity in this stage. SNR's in this stage of evolution have been observed at radio, infrared, optical and x-ray wavelengths. (3) Eventually the radiative losses from the SNR interior become significant, and the remnant enters the third, radiative stage of its evolution, when a shell-like structure is expected to occur. Much of the interstellar medium is at too low a density for the SNR to be observable in this stage. (4) Finally the SNR expands so far that its interior pressure drops to the point that the SNR merges with the ambient interstellar medium.

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