Mechanisms of supernova explosion: modern status

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Abstract The mechanisms of explosion of different type supernovae (SNe) are discussed. At least four mechanisms are under detailed inspection of scientific community for core-collapse SNe. They are the instability of standing accreting shock front that results in the large scale 3-dimensional hydrodynamic flows, the phase transition from nuclear to quark matter, the magnetic-rotational expulsion of supernova envelope, and rotational fission of collapsing stellar core into a pair of proto neutron stars. The mechanism of explosion of cosmological SNe (of Type Ia) is physically understood as the thermonuclear explosion of carbon-oxygen-helium matter. However there exists a serious problem with modeling of the structure and propagation of unstable thermonuclear flame that is crucial for numerical agreement with observations.

Keywords: Supernovae, Supernova Remnants

1. Introduction

Physically, there are two fundamental types of SNe: the thermonuclear SNe represented by Type Ia SNe (SN Ia) and the core-collapse SNe, respectively. The core-collapse SNe are subdivided into several subtypes depending on the amount of hydrogen hanging around the stellar core just before it begins to collapse such as Type IIP, IIn, IIb, Ib, and Ic SNe. The progenitors of Type IIP and IIn SNe have plenty of hydrogen in their envelopes, typically as much as $(10-15)\ M_\odot$. SNe IIn have also some hydrogen in an extended atmosphere formed by stellar wind on the top of their dense hydrogen enriched envelopes. The progenitors of Type IIL SNe have much less hydrogen, about $(0.1-1)\ M_\odot$ whereas the spectra of Type IIb SNe show only traces of hydrogen during the first few days after the explosion, then these SNe become similar to SNe Ib. Types Ib and Ic progenitors virtually have no hydrogen left. Type Ic differs from Ib by lack of helium. The Type Ic progenitors are believed to have lost not only all hydrogen but also a fair amount of helium during their evolution.

2. Thermonuclear SNe (Type Ia)

The type Ia SNe are believed to arise in close binary stellar systems from explosive carbon burning either in a degenerate carbon-oxygen (CO) white dwarf as soon as due to accretion it's mass increases to a certain value close to *Chandrasekhar mass* ($M \approx 1.4\ M_\odot$) or in the process of mergence of two white dwarf binary components. The explosion energy $E_{exp} \approx 10^{51}$ erg comes from the thermonuclear burning of ^{12}C and ^{16}O mixture into ^{56}Ni that has the maximum binding energy among nuclei with equal numbers of neutrons and protons. The white dwarf turns out to be totally disrupted in the explosion — no stellar remnant is left! The total energy of electromagnetic radiation $E_{rad} \approx 6 \times 10^{49}$ erg is mostly supplied by the $^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$ beta-decays. The hydrodynamic modeling of the SN Ia light curves shows that only a small fraction of explosion energy is transformed into radiation: $E_{rad} / E_{exp} \approx 0.06$. This is by a factor of 2 less than the ratio of the energy released per $^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Fe}$ beta decay (5.5 MeV) to the energy produced per synthesized ^{56}Ni (47 MeV) during the thermonuclear burning of the mixture of equal C and O mass fractions. This happens because a portion of beta decay energy is expended on the hydrodynamic expansion of supernova debris. Hence, almost all E_{exp} resides in the kinetic energy of the envelope expanding with the mean velocity ≈ 8 000 km/s. Comparison of the SN Ia models with observations shows that about (0.6 − 1) $M_{\odot}$ of ^{56}Ni is produced per SN Ia outburst.

The ignition of thermonuclear fuel and propagation of the flame in degenerate stellar matter is a fundamental problem still to be solved to understand the basic mechanism of SN Ia explosions and finally to calibrate SN Ia as standard candles for observational cosmology. From the beginning the thermonuclear flame propagates by means of a sub-sonic deflagration being governed by the electron thermal conduction. The burning front proves to be extremely thin and fraught with a number of instabilities such as Rayleigh–Taylor, Kelvin–Helmholtz and Landau–Darries ones. Since the Reynolds number typically is of the order of 10^{14}, the front gets a strongly wrinkled structure and the burning becomes of turbulent nature. Owing to the growth of surface area covered by the front the rate of combustion considerably increases. As a result, after a time the deflagration can develop into a super-sonic detonation that is driven by a shock wave which heats matter up to the ignition. The transition from the deflagration to detonation is required in order to achieve the compliance between theoretically predicted chemical compositions of the SN Ia ejecta and that observed in the SN Ia spectra. However, for a group of discovered recently sub luminous SNe Ia the deflagration alone seems to be adequate [1]. There is also a problem with understanding how and where the nuclear fuel actually begins to burn. The flame may flare up not necessarily in the very centre but either in an off center bubble or in separate little spots randomly distributed around. An extensive study of turbulent burning in degenerate matter of white dwarfs is under way. The current results and further references can be found in [1-9].

3. Core-collapse SNe

The iron stellar cores begin to collapse owing to the loss of dynamical stability. Due to the photo-disintegration of iron into free nucleons and α-particles the adiabatic index γ becomes less than the critical value 4/3. Hence, the gradient of pressure cannot withstand the force of gravity any more. An inner core with a mass of (0.6 − 0.8) $M_{\odot}$ around the stellar center begins to contract almost in a free fall regime. In a few hundredths of second the central density reaches the nuclear density and the contraction slows down. The outermost layers, being still in a state close to free fall, collide with the decelerated inner core. Thereby a nearly standing accreting shock wave (SAS) forms at the boundary of the inner core and the outer envelope. The key question for the core-collapse supernova mechanism is to verify whether such a standing shock becomes finally transformed into an outgoing blast wave that would expel the supernova envelope.

The SN outburst of core-collapse SNe is triggered by the gravitational collapse of the "iron" core of a mass M_{Fe}=(1.2–2) $M_{\odot}$ into a neutron star. About (10–15)% $M_{Fe}c^2$ is radiated in the form of neutrinos and antineutrinos of all flavors (e, μ, τ):

$$E_{\nu\tilde{\nu}} = (3\text{-}5)\times 10^{53}\,\text{erg.}$$

The explosion energy (kinetic energy of the envelope expansion) according to observations:

$$E_{exp} = (0.5\text{-}2)\times 10^{51}\,\text{erg.}$$

It comes from the shock wave created at the boundary between a new-born neutron star and the envelope to be expelled. So, for succesful explosion it is enough to transport in stellar envelope less than 1% of total neutrino energy $E_{\nu\tilde{\nu}}$:

$$E_{exp}/E_{\nu\tilde{\nu}} \sim 10^{-3} - 10^{-2}.$$

Figure 1 clearly demonstrates the formation of the SAS for the case of spherically symmetrical collapse of a 2 $M_{\odot}$ iron-oxygen stellar core [10]. At 0.123 s after the beginning of braking of the inner core contraction, nearly 1.8 $M_\odot$ is encircled by the SAS front.

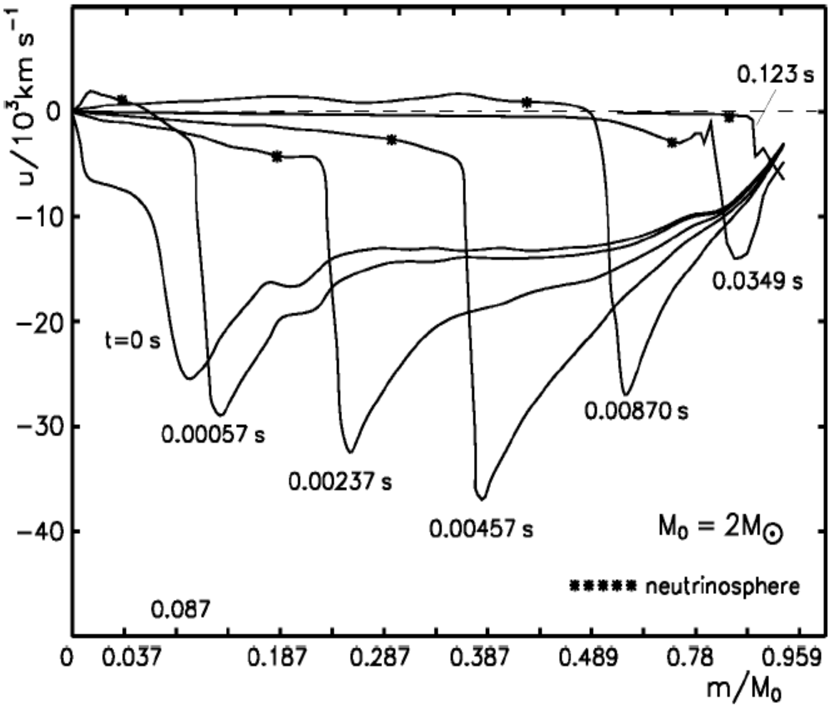

Fig1. *The velocity versus the relative mass m/M_0 at different times (Adapted from [10])*

Figure 2 shows the characteristic features of the hydrodynamic flow in the region around the neutrinosphere and SAS wave.

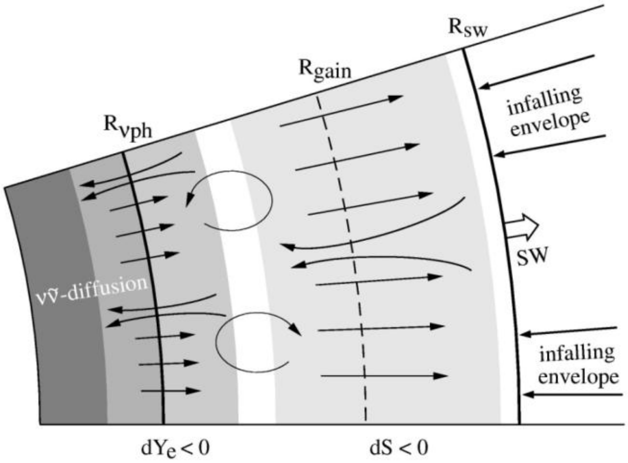

Fig2. *The layout of hydrodynamic flow in the interval between the shock wave (R_{SW}) and the neutrinosphere ($R_{\nu ph}$). Two regions of convective instability are shaded in light gray. At radii r > R_{gain} the heating of matter by the neutrino flux from the neutrinosphere exceeds the cooling by the local neutrino losses.*

The large scale convective currents are expected to evolve due to negative gradients of both the entropy ($dS < 0$, entropy-driven convection) that appears in the region just below the SW and of the electron fraction ($dY_e < 0$, lepton-driven convection) nearby the neutrinosphere. These currents transport some energy to the SW in addition to that supplied by the neutrino flux from the neutrinosphere. There was suggested that this effect can force the SW to propagate outside. However, an extensive modeling of the core-collapse SNe during last three decades has demonstrated that neither the convection nor the heating due to the neutrino flux (at $r > R_{gain}$, Fig. 2) can increase the explosion energy to the value that would be large enough to explain the observations. Nevertheless in case of spherically symmetric collapse, the SW finally throws an envelope out. This happens when with time the rate of mass accretion from the envelope considerably decreases and the excessive pressure like an over-compressed elastic spring pushes the SW outward forcing it to propagate through a steep density gradient. Unfortunately, this effect (called a hydrodynamic bounce) can produce only a low energy explosion with E_{exp} being at least one or even two orders of magnitude less than its standard value of 10^{51} erg. Although such a weak explosion seems to be adequate for some sub luminous Type II SNe like the historical Crab nebula SN 1054 (see [11] and discussion therein), the problem how to get the more energetic explosions remains to be far from a satisfactory solution, at least in the framework of spherically symmetric models.

Therefore, it is plausible to assume that the solution can be found by addressing to substantially non-spherical effects such as, for instance, magneto-rotational mechanism [12–14] and rotational fission of the collapsing core into a binary system of proto-neutron stars that evolves losing angular momentum and energy through the gravitational waves with subsequent explosion of a low-mass ($\approx 0.1M_{\odot}$) component [15 –18].

During the last years it became clear that the spherically symmetrical SN models can, nevertheless, explode due to the phase transition from nuclear to quark matter if the transition occurs *after* the SAS formation. Figure 3 shows an example of detailed hydrodynamic calculations [19] (see also [20]). The formation of SAS completed at 240.5 ms (thick black solid line). Then the phase transition appeared at radius about 8 km and initiated further gravitational contraction of stellar interiors that produced new shock wave propagating outwards. At 256.3 ms this shock wave reaches SAS pushing it far off the accreting envelope and thereby triggering the supernova explosion. A very important result of calculations in [19] is also the prediction of a narrow (~1 ms) peak of electron antineutrino flux with mean square antineutrino energy up to 35 MeV. The peak occurs at 256–257 ms. Such a peak can be observed by modern neutrino detectors for the SN in our Galaxy.

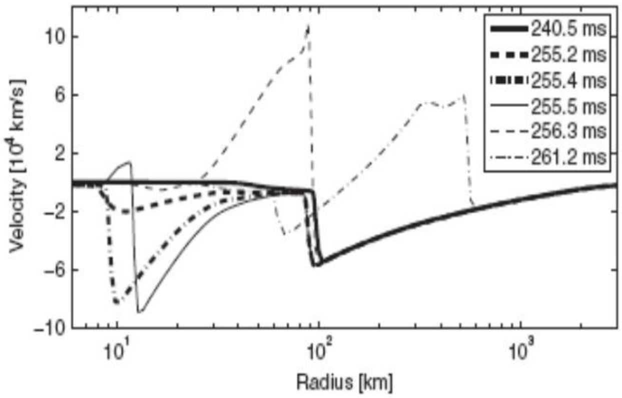

Fig3. *The supernova explosion induced by the phase transition from nuclear to quark matter inside a spherically symmetrical stellar core [19].*

Another possibility to obtain the SN explosion for initially spherically symmetrical presupernova model is connected with the SAS instability (SASI) with regard to 2D and 3D perturbations. The instability strengthens the convective currents in the gain region under the SAS front (Fig. 2) allowing them to penetrate into the accreting flow and to transport there more energy thereby facilitating the expulsion of the supernova envelope. The SASI is under careful examination by scientific community already many years [21–26].

3.1. The supernova 1987A in the Large Magellanic Cloud

The most outstanding issues of the SN 1987A are

(i) the detection of extragalactic neutrinos,
(ii) the discovery of radioactive nuclides (^{56}Ni, ^{56}Co, ^{57}Co, ^{44}Ti) in the SN ejecta,
(iii) the recognition of the decisive significance of large-scale mixing just before or in the process of the explosion and of nonspherical effects.

Theoretical deciphering of the SN 1987A neutrino signal is not yet completed. The rotational fragmentation model is the only one that combines two, separated by 4.7 hours, neutrino signals in one self consistent scenario [15–18]. Recent observations of the intrinsic dusty ejecta of SN 1987A in the infrared line (1.644μ m[SiI]+[Fe II]) [27] showed that the dust, screening central point source, has the shape of a prolate ellipsoid laying in the plain perpendicular to the axis of rotation – exactly as the rotational fragmentation model predicts.

The crucial point here is the long-awaited discovery of a stellar remnant (a neutron star or a black hole) which emergence out of the supernova debris is expected in the near future. At present, only upper limits on the optical and X-ray luminosities of the SN 1987A central point source are available [28].

4. Conclusion

For lack of space, several important topics were not discussed in this extremely short review. Among them is the connection of SNe with gamma-ray bursts, the onset of a neutrino-driven wind that presumably should blow from a nascent hot neutron star, and the nucleosynthesis in SNe (in particular, the neutrino-induced nucleosynthesis and r-process in a core-collapse SNe). To make up this deficiency we refer the reader to the excellent reviews [29 – 33].

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