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Abstract. Mechanisms of explosion for supernovae are considered. It is shown that large-scale convection is the crucial physical process for evolution of explosion. Neutrino luminosity is estimated for SN II. The structure of supernova envelope and jet was calculated.

Keywords: supernovae, neutrino luminosity, nucleosynthesis, large-scale convection.
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INTRODUCTION

Over the last several decades, numerous attempts have been made to explain the supernova explosion (SN). In 1960, Fowler and Hoyle [1] suggested two mechanisms for the explosion of a star. First mechanism is connected with the development of a thermal outburst outside degenerate core of star. Second mechanism is based on collapse of central core. In the present work we develop these ideas.

RESULTS AND DISCUSSION

We begin from thermal instability. According to current concepts, a type Ia supernova is associated with a thermal outburst in the degenerate core of the presupernova. The theory of thermal outbursts was developed about half a century ago. In 1974, a model of deflagration SN was suggested in [2], where the numerical method for hydrodynamic calculations of the dense stellar core explosion directly included the kinetics of thermonuclear fuel burning.

The results of calculations for velocity profile vs mass coordinate are shown on Fig 1. In 1999, it was shown that a detonation wave cannot develop in the degenerate CO core of the presupernova: this wave decays into a shock and a slow combustion front [3, 4] (Fig. 2).

This result immediately demand new explanations of both the mechanism of the observed explosions and the nucleosynthesis of heavy elements. In what follows, the theory of explosion in CO core approached the problem of the transition from slow combustion to an explosion from two directions.

The first suggested that the acceleration of the deflagration front is due to the development of hydrodynamic instabilities, such as Rayleigh–Taylor or Darrier–Landau instability. Other studies using this approach consider acceleration of the front due to pulsation instability, delayed detonation, and fast particles, including neutrino ignition [2, 5]. Burning of the first fraction of carbon ($\Delta M_1 / M \approx 2.3\%$) excites radial pulsations of the star in which the expansion phase is followed by the contraction phase. The amplitude of the first oscillation is already large enough because the effective adiabatic index is close to the critical value 4/3. At the contraction phase burning is renewed and the second fraction of carbon is burnt ($\Delta M_2 / M \approx 8.7\%$). The expansion again damps down thermonuclear burning and all is repeated in the same sequence [2].

The other approach considered the development of large-scale convection. For a long time, only spherically symmetrical burning of the white dwarf was considered in scenarios for supernova explosions. However, authors of [6] showed that light material burnt in the core of a presupernova can float upward in the form of large bubbles, and the white dwarf's explosion should display dramatic deviations from spherical symmetry. The buoyant force pushes a bubble of burnt material out of the centre faster then the flame propagates. In such a supernova explosion in the core of a cool carbon–oxygen white dwarf, multiple ignition of thermonuclear reaction occurs. The successive thermonuclear outbursts can essentially result in the establishment of a detonation regime.

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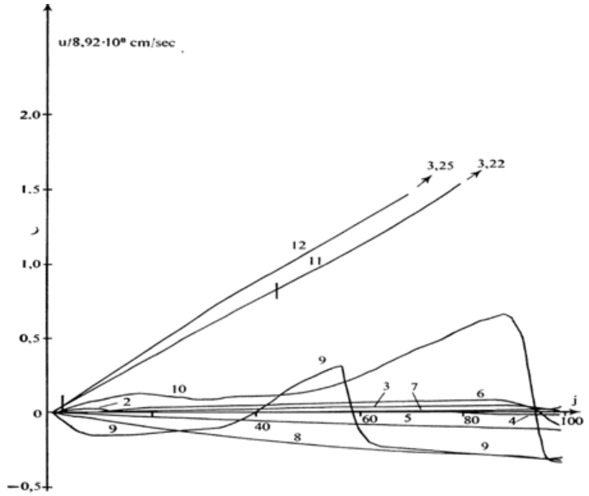


FIGURE 1. Velocity u profiles at various instants in time t_i against the number of the mass zone j. At the instant t_1 the velocity $u \equiv 0$.

Later, numerical simulations of thermonuclear supernovae [7] supported this qualitative conclusion. For example, Fig. 3 presents typical entropy contours in an exploding white dwarf. The rising of bubbles is of prime importance for the theory of supernovae.

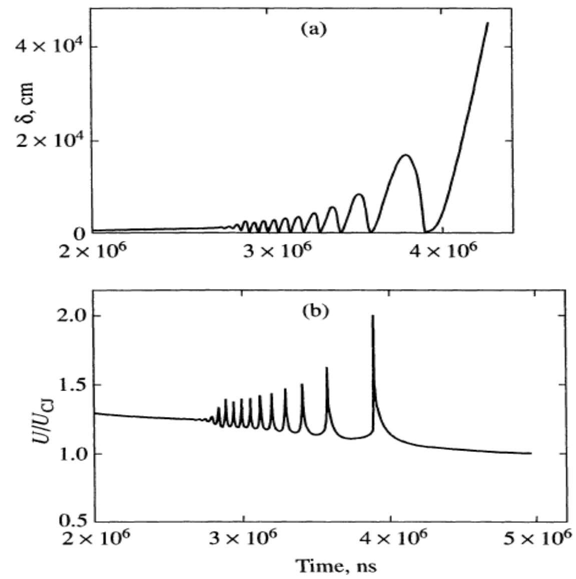


FIGURE 2. The width δ of the reaction zone (a) and the degree of deceleration $f=U/U_{CJ}$ of the shock wave (b) as a function of time.

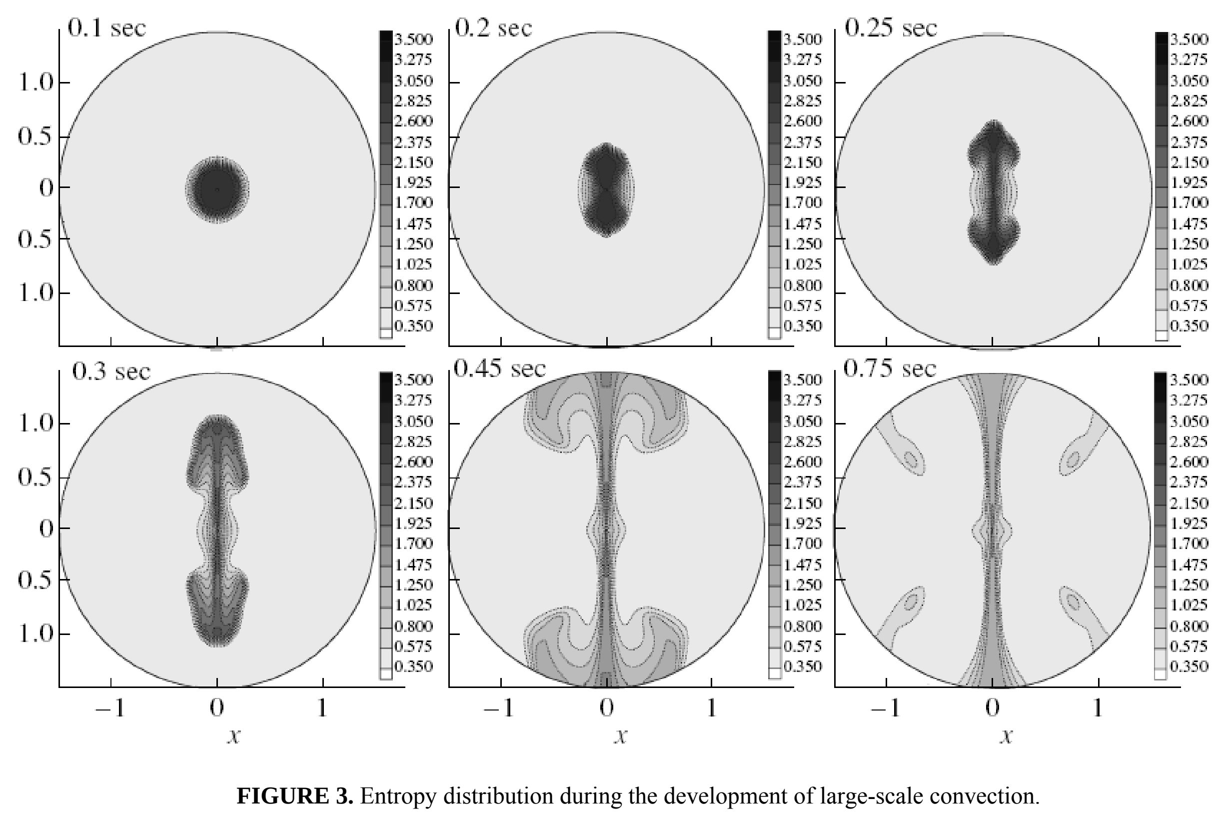


FIGURE 3. Entropy distribution during the development of large-scale convection.

The formation of large bubbles and their subsequent rising is of crucial importance for many physical and technical applications, such as inertial thermonuclear synthesis and the physics of high energy densities and combustion, as well as for other problems in astrophysics For example, when a flame front propagates in a gravitational field, the light products of the burning form a bubble, increasing the surface area of the flame front and the rate of combustion.

For the case of a thermonuclear supernova, our study shows that the main feature of the thermonuclear explosion of the rotating CO core of a type I presupernova is large-scale convection, which develops in the form of giant bubbles of burnt material rising towards the surface of the core. This suggests that a type-I supernova explosion should be aspherical.

In this case, the nucleosynthesis of elements will differ from calculations made using spherical models. The energy parameters usually applied for cosmological estimates will also differ. Another essential conclusion of our study is the possible dependence of the observed parameters of supernovae on the initial rotation of the presupernova core.

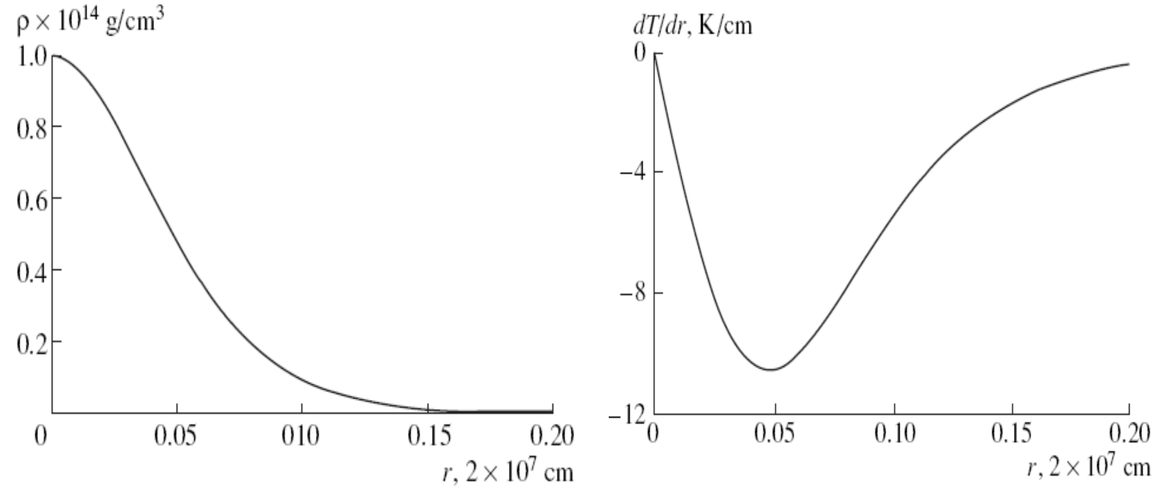
Now we consider collapse model. Over the last several decades, numerous attempts have been made to explain the formation of neutron stars as a result of type II supernova explosions; i.e., as a result of core collapse in massive stars. This question was first considered in [8], where the results of numerical simulations of such an explosion were presented. The action of neutrino emission from the core on infilling stellar envelope was taken into account, leading to ejection of the envelope. An important element of this model is the bounce shock, which is formed as a result of the rapid compression and deceleration of matter at the nuclear densities of the collapsing core. However, subsequent numerical simulations of supernova explosions led to certain difficulties in the proposed model. Imshennik and Nadezhin [9] showed that matter becomes opaque to volume neutrino emission at the central densities characteristic for the collapse regime. Assuming that neutrinos leave the proto-neutron core in a diffusion regime, we can find the characteristic time for their escape, which is of the order of 10 s. In this case, the neutrino emission is not able to support the bounce shock, which is stopped and transformed into an accretion wave. In addition, the mean energy of neutrinos is decreased during their diffusion, likewise making ejection of the envelope improbable. In [9] and subsequent works of D. K. Nadezhin, numerical simulations of the collapse of iron cores with masses of 2 and 10 $M_{\odot}$ were carried out, taking into account all the physical processes in the stellar material. In these simulations, either the supernova envelope was not ejected, or it was ejected with an energy substantially below observed values. Instead of the expected neutron star, the core collapse led to the “silent” formation of a “black hole.” This raised the question of the departure velocity and mean energy of the neutrinos produced in type II supernovae.

Currently, two mechanisms for a supernova envelope ejection are usually considered. The first supposes the rapid ejection due to passage of a shock through the envelope. The second mechanism supposes heating of matter behind the shock front due to the flux of neutrinos from the neutrinosphere, which facilitates the motion of the shock and the ejection of the envelope. However, computations have shown [10] that these two mechanisms are inefficient for several reasons. In the first model (the so-called fast mechanism), the shock loses some of its energy to split iron-group nuclei into free nucleons, as has been confirmed by the results of [9]. In addition, when the shock reaches the surface of the neutrinosphere, neutrinos begin to carry away some of its energy. The pressure in the shock is decreased, and the shock is weakened and ceases to move in the inward flux of matter [10]. The action of the second mechanism is determined in many ways by the conditions in the region between the neutrinosphere and the shock, and depends appreciably on the luminosity and mean spectral energy of the neutrinos. The required neutrino luminosity can be obtained only due to convection inside the neutrinosphere. This convection, in turn, can only develop if the heating of matter and the formation of a region of instability near the neutrinosphere occurs more rapidly than the motion of matter from the shock to the surface of the proto-neutron star. In this case, we are speaking of convection on small scales, much smaller than the stellar core. In addition, the energy stored in the neutrinosphere is too low to eject the supernova envelope.

During the collapse of the iron core, about 99% of the gravitational energy of the forming neutron star goes into the energy of the electron gas, and is then carried away by neutrinos. To eject the stellar envelope, some of this energy must be transferred to the outer layers of the star by some efficient and rapid mechanism. Convection both inside and outside the neutrinosphere can increase the transfer of energy to the shock front. However, certain conditions are required for this convection to occur. For example, the characteristic time for the development of the convection must be shorter than the time scales for accretion and the transfer of energy to neutrinos. In addition, convection requires a constant source of energy.

We propose a new mechanism for the rapid escape of neutrino flux associated with large-scale hydrodynamic instability in the proto-neutron star [11]. This instability is manifest on a very short time scale (of the order of $10^{-3}-10^{-1}$ s), and can bring about the ejection of the envelope via rotational energy and increase in the neutrino flux.

We have carried out numerical simulations of large-scale instability in a proto-neutron star for the case of large jumps in density. The main equations and numerical method are described in detail in [12]. The computations were conducted using nested grids. The depth of the nesting of the grids reached six levels, in contrast to the previous computations [12], where the nesting depth was only three levels. The initial density at the stellar centre was taken to be 2×10^{14} g/cm^3. The equation of state of the matter was taken from [13]. The initial density distribution was computed assuming that the presupernova core was stationary; the result is presented in Fig.4a. Figure 4b shows the temperature gradient brought about by the non-equilibrium neutronization of the matter at the centre of the proto-neutron star after the collapse is stopped.



(a) (b)

FIGURE 4. Initial distribution of density (a) and initial temperature gradient (b).

The initial distribution of the dimensionless entropy is presented in Fig. 5a. In these computations, the distance was scaled to the value 2×10^7 cm. We took the region of instability to be perfectly spherical at the initial time. However, as it rises, the matter with enhanced entropy (bubble) is stretched along the rotational axis of the star, in accordance with the predictions of the analytical theory [7]. It is shown on Fig. 5b.

The time for the formation of large-scale convective structure is about 4−5 ms. By this time, the bubble apex reaches the radial distance of $x_0 = 2\times 10^5$ cm, and the ascent velocity of the bubble is of the order of $(2-4) \times 10^8$ cm/s. The mushroom instability that is typical for dynamical bubbles has not formed at this time.

Figure 5c presents computations for 6 ms, by which time the bubble has reached a radial distance of 4×10^5 cm for a density of the surrounding matter of $\sim 9\times10^{13}$ g/cm^3. The leading edge of the bubble shows signs of the development of the mushroom instability, and the local density of matter in the bubble has decreased to 2.3×10^{13} g/cm^3.

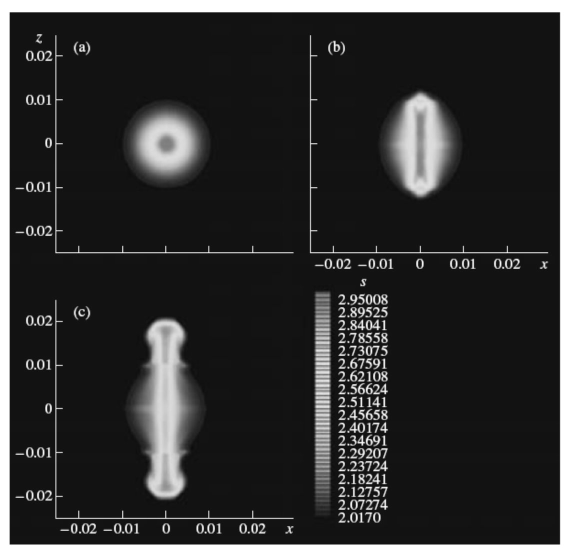


FIGURE 5. Distribution of the dimensionless entropy during development of convection.

The next important point in the model is the computation of the neutrino emission at the surface of a convective bubble as a function of time, i.e., as a function of the bubble's position in the star as it rises. The spectra and intensity of the neutrino emission of a rising bubble were computed from a central density 2 × 10^{14} g/cm^3 to low density in [14]. The kinetic equation for the neutrino distribution was solved, imposing boundary conditions at the bubble surface and allowing for the varying density. The method used to solve this kinetic equation is based on a moment approximation. The first two moments describing the momentum and angular distributions of the neutrinos were used in the solution. A detailed description of the method can be found in [14]. We carried out additional computations using this method in our own study. Fig. 6 presents the mean neutrino energy at the bubble surface as a function of time. Computation results are given for three initial sizes d_0 of the convective bubbles. We can see from Fig. 6 that this mean neutrino energy is 30–80 MeV for times of 2−5 ms. Neutrinos with energies of 30 and 50 MeV have mean free paths of l = 5.67 × 10^6 cm and 2.044 × 10^6 cm, respectively. These estimates indicate that high-energy neutrinos from the bubble surface reach the shock and support its intensity. The initial size of the convective structures that are formed also influences the mean energy of the emitted neutrinos. We used the mean neutrino energies obtained when computing the interaction of the neutrinos with the shock.

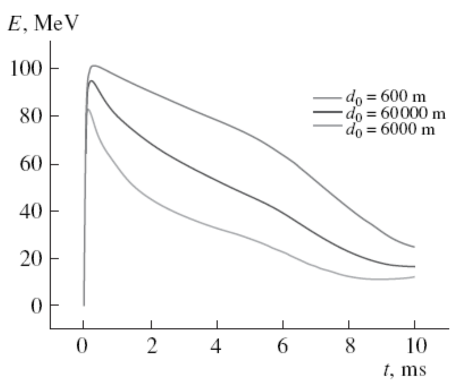


FIGURE 6. Mean neutrino energy at the bubble surface as a function of time.

The escape of high-energy neutrinos from the central dense layers of the pre-supernova results from the large-scale convection. In this case, the highest intensity of high-energy neutrinos is along the rotational axis of the star. Results of computations were shown fig. 7. One can see, that the shock develops more rapidly along the rotational axis, since it obtains energy from the high-energy neutrinos. At the same time, since there is virtually no neutrino flux in the equatorial plane, the shock is stopped and transformed into an accretion wave.

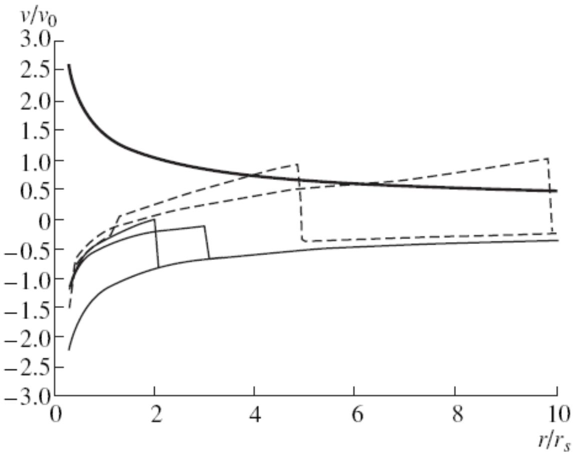


FIGURE 7. Velocity profile at some instant: dashed is along the rotation axis, solid is perpendicular to it. Thick line represent parabolic velocity.

It is seen that the matter reaches the escape velocity along the rotational axis. Thus, the ejection of matter and the supernova explosion becomes possible. It is important that, in this case, the velocity and density distributions of the envelope are very asymmetrical. The kinetic energy of the envelope, which has been ejected with a speed exceeding the escape speed, reaches 5 × 10^{51} erg.

Due to development of large-scale convection, our numerical experiment leads to a very asymmetric explosion, primarily along the rotational axis of the star for SN I and SN II. Subsequent hydrodynamic computations will show the influence of this geometry on the structure of the supernova envelope for two types. These models have important implications for the detection of neutrinos from supernova explosions, light curve of type Ia, and nucleosynthesis.

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