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Rotational explosion mechanism for collapsing supernovae and the two-stage neutrino signal from supernova 1987A in the Large Magellanic Cloud

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Abstract. The two-stage (double) signal produced by the outburst of the close supernova (SN) in the Large Magellanic Cloud, which started on and involved two neutrino signals during the night of 23 February 1987 UT, is theoretically interpreted in terms of a scenario of rotationally exploding collapsing SNs, to whose class the outburst undoubtedly belongs. This scenario consists of a set of hydrodynamic and kinetic models in which key results are obtained by numerically solving non-one-dimensional and nonstationary problems. Of vital importance in this context is the inclusion of rotation effects, their role being particularly significant precisely in terms of the question of the transformation of the original collapse of the presupernova iron core to the explosion of the SN shell, with an energy release on a familiar scale of 10^{51} erg. The collapse in itself leads to the birth of neutron stars (black holes) emitting neutrino and gravitational radiation signals of gigantic intensity, whose total energy significantly (by a factor of hundreds) exceeds the above-cited SN burst energy. The proposed rotational scenario is described briefly by artificially dividing it into three (or four) characteristic stages. This division is dictated by the physical meaning of the chain of events a rotating iron core of a sufficiently massive (more than $10M_{\odot}$) star triggers when it collapses. An attempt is made to quantitatively describe the properties of the associated neutrino and gravitational radiations. The review highlights the interpretation of the two-stage neutrino signal from SN 1987A, a problem which, given the present status of theoretical astrophysics, cannot, in the author's view, be solved without including rotation effects.

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1. Introduction. Supernova 1987A in the Large Magellanic Cloud

1.1 Neutrino signals and their theoretical interpretations

On 23 February 1987, four underground neutrino detectors located at different places on Earth registered the series of extremely rare events concentrated near two instants of time separated by a long 4.7-hr (16,920 s) time interval. These two series (two signals) themselves included several momentary triggerings of the detectors with an energy release in each event of about 10 MeV and a duration of about 10 s. The first signal was reliably detected at 2 h 52 min UT by the Soviet–Italian LSD (Liquid Scintillation Detector) detector [1–3] and also noted by the Japanese KII detector [4]. One day later, optical astronomers discovered a supernova in the Large Magellanic Cloud (LMC) dubbed SN 1987A (see review [5]). The second neutrino signal was even more reliably registered at 7 h 36 min UT by the KII and IMB (USA) detectors [6, 7], as well as by the Soviet BUST (Baksan Underground Scintillation Telescope) detector [8].

It is the second neutrino signal that very rapidly was theoretically interpreted, since it more or less corresponded to the 'standard' model of iron core collapse in a star with mass $M \geqslant 10M_{\odot}$. The model is based on the one-dimensional hydrodynamic theory of the collapse elaborated long before the detection of the neutrino signals from the famous supernova outburst in LMC [9–12]. In this theory based on numerical calculations, neutrino emission from the collapsing stellar core matter determines the energy characteristics of the collapse and has been the most important physical factor of the model. We note from the very beginning that the instant of appearing the second neutrino signal almost coincided with the theoretical estimate of the time of energy release in the explosion (almost instantaneous) at the center of the presupernova star, which followed from comparatively simple hydrodynamic calculations of the shock wave propagation throughout the presupernova envelope. Remarkably, astronomers observed the presupernova of SN 1987A long before its explosion for the first time in the history of detecting supernova outbursts, so these calculations made use of the known data on the structure of the stellar envelope (see review [5]). In contrast, the instant of time of energy release in the explosion has been impossible to connect with the instant of first neutrino signal: the time delay could not exceed one-two hours. Thus, the problem of the theoretical interpretation of the first neutrino signal appeared nearly 20 years ago. In addition, the significance of the first neutrino signal is supported by the following fact: during the entire time of operation of the LSD prior to 1999, no signal with characteristics similar to those from SN 1987A had been detected; likewise in the two-year interval before that [13, 14]. However, skepticism constantly grew over these years with regard to the standard theoretical model of the collapse that assumes the one-dimensional character of this process, since this model has provided no explanation for the huge explosion that follows the collapse in the observed supernovae [15, 16].

In fact, the standard model has now significantly changed to become a model with another explosion mechanism, the neutrino-convective one, two-dimensional, by the way, elaborated in several papers [17–19]. Unfortunately, these calculations remain less than fully convincing (not restricting ourselves to the consideration of collapsing stars of minimal possible mass). So, it became necessary to consider in the theory of collapse and explosion other non-one-dimensional effects, including rotation effects. Simple estimates in paper [12] already showed how rapidly the rotational energy increases during the collapse ($\propto r^{-2}$) in comparison with the gravitational energy ($\propto r^{-1}$), under the only plausible assumption that the specific local angular momentum is conserved. For a characteristic compression of a star's core along its radius by ~ 100 times, this integral energy became comparable to the gravitational one, while being 100 times smaller than the gravitational energy in the initial conditions. In other words, accounting for rotation could significantly affect the iron core collapse for very moderate initial parameters of core rotation, which was preserved in the interiors of the star during its evolution from the gas–dust cloud (during the so-called initial stellar collapse).

1.2 First models of rotational collapse and explosion

Since 1992 [20], we have been attempting to introduce the rotation effects in the model of the iron core collapse. In this paper, the non-one-dimensional problem was reduced to the one-dimensional one by averaging the centrifugal force over the polar angle counted from the rotational axis. This problem was first addressed as early as 1977 [21] with the purpose of preserving all the complex physics of the one-dimensional hydrodynamic theory of collapse of nonrotating stars from papers [22, 23] which underlie the standard model. A comparison of the results of papers [21] and [22] allowed us to understand the relative role of the rotation effects during the collapse. These calculations in Ref. [21] (later and more detailed calculations can be found in Ref. [20]) lasted several seconds from the beginning of the collapse until the neutrino energy losses resulted in the formation of a low-temperature rotating neutron star with high central density ($\sim 2 \times 10^{14}$ g cm^{-3}), which is only slightly below the final densities of nonrotating neutron stars [22]. In brief outline, the rotation resulted in cold collapse in the direct sense of the word, since the main contribution to the pressure at the star's center was due to degenerate ideal electron and neutron gases.

In the physical setting of the problem under consideration [20, 21], we needed, of course, to preset some rotation of the iron stellar core for the initial conditions. Naturally, the question arises as to the origin of this rotation, although, as mentioned above, a rather moderate value is needed. Most likely, this rotation was preserved from the very origin of the star. This means that in the due course of the very long thermonuclear evolution (many millions of years for a star with mass in excess of $10M_{\odot}$) the primordial rotation was conserved and was not lost due to the possible mechanisms of the angular momentum loss. Unfortunately, the theory of stellar thermonuclear evolution does not provide the required initial parameters of rotation, since quantitative account for the rotation effects until recent time was given in a rather approximate fashion due to their complexity. Nevertheless, there are serious restrictions on the initial rotation set by the evolution process in the form of a solid-body radial distribution of the angular velocity, since at the final evolutionary stages convective instability inevitably develops in the central parts of massive stars. This instability allows only the solid-body rotation law, and the rotational velocity at the equator must necessarily be smaller than the parabolic one. These initial conditions for the rotation of the iron stellar core were discussed in detail in our paper [24], in which the hypothetical rotational mechanism of the core collapse supernova explosion was proposed. It is the result of a sufficiently strong initial rotation of the iron stellar core (with the upper bounds discussed above).

Finally, it is worth specially emphasizing that our choice of a nonzero initial rotation is frequently used to criticize the proposed rotational mechanism of explosion and theoretical interpretation of the double neutrino signal from SN 1987A that follows from it. The response to this criticism was partially done above, but also a counter question is possible. Is it possible to assume that the core of the presupernova of SN 1987A has no significant initial rotation? Of course, the comparatively small energy of the assumed rotation should be borne in mind.

1.3 Qualitative description of the rotational mechanism of collapsing supernova explosions — rotational scenario for the SN explosions

In papers [24–26], we proposed and qualitatively described the rotational mechanism of collapsing supernova explosions. It was especially discussed in Ref. [26] in detail and apparently self-critically. This mechanism, which is realized as a set of models, can be called a rotational scenario of the explosion. According to this hypothetical scenario, the key role is played by multidimensional hydrodynamic models of the collapse and explosion, which consecutively take account of known physical properties of matter under extreme conditions inside stars (the equation of state and nuclear composition), as well as the physics of the neutrino emission (all possible beta-processes between free nucleons and atomic nuclei) [27–33]. Here, we have mentioned in parentheses only basic physical properties and processes, but this does not imply that the physical setting of problems in these models was limited by these properties only.

It is important to realize that merging the sequence of these models into the unified (through) model of the collapse and explosion is principally impossible. This beggars fulfillment due to a qualitative difference in their physical and mathematical features, as well as due to the danger of losing the transparency of the results of, generally speaking, the numerical solution of problems in these models. But this is exactly the distinctive feature of the scenario approach, which is very widespread both in astrophysics and theoretical physics in general, with its permanent reference to experimental physical data.

The suggested rotational mechanism of supernova explosions also includes a very important problem of celestial mechanics: the three-dimensional problem of the evolution of a binary neutron star system under the action of emission of gravitational waves [34–36], as well as this problem in combination with the additional account for mass exchange between the components of the binary system [37]. It should be specially stressed that it is the (mostly analytical) solution to this problem that allows us to give the theoretical interpretation to the two-stage neutrino signal from SN 1987A. Such an interpretation, of course, necessarily assumes that the scenario considered implies the explanation of the collapse transformation into an explosion with the energy release as observed in the core collapse supernovae. We can say even more decisively: without an explanation of the observed parameters of supernova outbursts, their energy release above all, which in most cases is astonishingly close to 10^{51} erg, any interpretation of the observed two-stage neutrino signal from SN 1987A loses obviously its meaning [13, 14].

2. The qualitative description of the rotational explosion scenario in the case of SN 1987A

2.1 Rotational iron stellar core collapse and formation of the rotating collapsar as a first neutrino signal source

Strictly speaking, the model of the collapsar with a given initial rotation must be two-dimensional, axially symmetric from the very beginning. However, its distinctions from the spherically symmetric model must be very small until the instant of formation of the dense neutron star. These distinctions can be especially small near the star's center due to the imposed solid-body rotation law. For this reason, a satisfactory description of the collapse can most likely be obtained using a quasi-one-dimensional model [20], including the calculation of the neutrino radiation with its strong concentration towards the star's center. It is important to note that during the collapse the stellar interiors gradually become opaque to neutrino emission. The quasi-one-dimensional model allows the most rigorous means for taking into account the opacity effect because in this case there is an analytical solution to the neutrino and antineutrino transport equations, proposed as early as in paper [12] and realized in our paper [33] during the calculation of neutrino and antineutrino spectra which are so important in comparing the model and observations.

The main result of these model computations is that the structure of the stationary rotating collapsar is subjected to the well-known dynamic instability with respect to azimuth perturbations if the dimensionless parameter of the ratio between integral energies, $\beta = E_{\rm rot}/|E_{\rm grav}|$, exceeds some critical value. One can adopt (faut de mieux) the instability condition in the form of the classical inequality $\beta \geqslant 0.27$ [38], which is partially confirmed by numerical calculations [39] even for a rotating collapsar with a realistic equation of state. Under this strong assumption, a rather wide region of model configurations of axially symmetric neutron stars was calculated in Ref. [40] in the plane of integral parameters M_0 (the total mass) and J_0 (the total angular momentum) satisfying this criterion. Only two these parameters can be undoubtedly considered as constant until the instant of complete development of the nonlinear stage of the dynamic instability in the rotating collapsar. In the most interesting case of developing the preferential $m = 2$ mode instability at the nonlinear stage, one can expect the formation of a binary system of two neutron stars, which we shall discuss below in Section 2.2. Note from the very beginning that the gravitational radiation effects, as well as other general relativity (GR) effects, do not virtually affect these instability conditions.

The above-described process of the collapse development is very short, and after several seconds of neutrino cooling ends up with the stage of the emergence of a stationary rotating collapsar, which, in our opinion, is the main source of the first neutrino signal registered by the LSD. But as we showed in paper [13] by the analytical estimate of neutrino spectra, such an interpretation of the observed neutrino signal would require the total absence of absorption (deposition) of neutrino radiation from central regions of the collapsar. New calculations [41] made in the framework of the quasi-one-dimensional model [20] indeed reproduce the appropriate electron neutrino spectra with an average energy of 35 MeV exactly in the case of total ignorance of the deposition effect. With account for this effect, calculations [33] yielded a mean electron neutrino energy of only 13 MeV.

Figure 1 illustrates for comparison the integral (integrated over time) spectra of the electron neutrino and antineutrino, both in the case of rigorous accounting for the neutrino radiation deposition [33] and in the case of its absence [41], which were obtained, let us recall, in quasi-one-dimensional hydrodynamic models. In Fig. 1, spectra $F_{\nu}^{i}(E)$ and $F_{\bar{\nu}}^{i}(E)$ ($i = 1, 2$ with $i = 1$ and $i = 2$ corresponding to taking into account and ignoring the deposition effect, respectively) are dimensionless quantities, since they are calculated by the time integration of the instantaneous neutrino and antineutrino energy spectra with the dimension c^{-1}. So their proper integrals (now over energy) immediately give the total energies carried by these particles during the total duration of the signal from the rotating collapsar. They are $\Phi_{\nu}^{1} = 2.69 \times 10^{52}$ erg, $\Phi_{\bar{\nu}}^{1} = 5.43 \times 10^{51}$ erg (a difference of 4.95 times), and $\Phi_{\nu}^{2} = 3.14 \times 10^{52}$ erg, $\Phi_{\bar{\nu}}^{2} = 1.70 \times 10^{51}$ erg (a difference of 18.5 times), respectively. Remarkably, the total energies $\Phi_{\nu}^{i} + \Phi_{\bar{\nu}}^{i}$ changed extremely little, just as the ratio $\Phi_{\nu}^{2}/\Phi_{\nu}^{1} = 1.17$ did for the neutrino.

It should be added that the contribution from the electron antineutrinos can be neglected relative to that from the electron neutrinos, especially as obtained in calculations

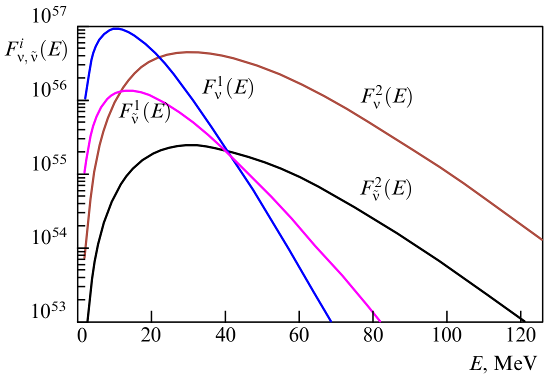

Figure 1. Integral spectra of electron neutrinos (ν) and antineutrinos ($\tilde\nu$) obtained by integrating instantaneous energy spectra over the whole mass of the collapsing iron core of a star (total core mass $M_0 = 1.8M_\odot = 3.58 \times 10^{33}$ g) taking into account rotation (the total angular momentum $J_0 = 6.91 \times 10^{49}$ erg s and the initial circular frequency $\omega_0 = 1.82$ s^{-1}) and over all time until the instant of formation of a stationary rotating collapsar, according to hydrodynamic models (in the quasi-one-dimensional approximation) from papers [33, 41]. These spectra $F^i_\nu(E)$ and $F^i_{\tilde\nu}(E)$ have the physical sense of the energy spectra (being nondimensional quantities with the formal dimension erg erg^{-1}). The superscript $i = 1$ marks the calculations with a rigorous account for the neutrino deposition effect [33], and the superscript $i = 2$ shows calculations without neutrino deposition [41]. The energy of the neutrino or antineutrino is plotted on the abscissa in MeV, so the further integration of these spectra over energy should take into account the factor 1.602×10^{-6} to obtain the total energy of the neutrino signal in ergs (see the text for the total energy estimates).

[41]. Incidentally, due to this fact other underground detectors did not 'see' the first neutrino signal from SN 1987A. However, the presence of a large amount of iron in LSD with its specific sensitivity to electron neutrinos [13, 42–44] played the decisive role in the recording of the signal by this detector.

In Table 1 borrowed from Ref. [13] we give the estimated number of events in each of three detectors, assuming a monochromatic neutrino signal at 40 MeV (column N_1), estimates with account for the detection efficiency η of the event (column $N_1\eta$), and estimates obtained assuming the analytical neutrino spectrum (column N_2 with the parameter $\varphi = 7.5$). Finally, in the last column of Table 1 we present the number of events observed by LSD on 23 February 1987, which should be compared with figures from the previous column.

In paper [41], neutrino emission spectra $F^2_\nu(E)$ were obtained from a numerical model of the collapse, i.e., they were fully consistent with all thermodynamic parameters of the collapsar. The theoretical estimate of the number of events N_ν in the LSD is given using the elementary formula in which the integral spectra of neutrino emission $F^2_\nu(E)$ are obviously substituted:

$$N_\nu = N_{\mathrm{Fe}} \frac{\eta\xi\zeta}{4\pi d^2} \int_0^\infty \sigma_{\nu\mathrm{Fe}}(E_0) \left(\frac{E}{E_0}\right)^2 F^2_\nu(E)\, \frac{\mathrm{d}E}{E}\,, \tag{1}$$

where N_{Fe} is the number of iron nuclei in the LSD, d is the distance to LMC, η is the detection efficiency of events on LSD, $\sigma_{\nu\mathrm{Fe}}(E_0)$ is the cross section of the nuclear reaction $\nu + {}^{56}\mathrm{Fe} \to \mathrm{e}^- + {}^{56}\mathrm{Co}$ for the neutrino energy E_0, and $F^2_\nu(E)/E$ is the number of neutrinos with energy E in the integral spectrum. In the integral over the neutrino energy the characteristic quadratic energy dependence of the neutrino cross section [42, 43] is also utilized. Factors ξ and ζ before the integral sign have the physical meaning of the relative contribution from neutral currents and the additional contribution of carbon nuclei to the total cross section in the LSD detector, respectively. We substitute into formula (1) the following values of above-introduced quantities: $N_{\mathrm{Fe}} = M_{\mathrm{Fe}}/56m_0 = 2.15 \times 10^{30}$ with the total iron mass $M_{\mathrm{Fe}} = 200$ t (m_0 is the atomic mass unit), $d = 50$ kpc $= 1.55 \times 10^{23}$ cm, $\eta = 0.6$, $\xi = 1.3$, $\zeta = 1.3$, and $\sigma_{\nu\mathrm{Fe}}(40\text{ MeV}) = 4.23 \times 10^{-40}$ cm^2. The integration over the spectrum in formula (1) yields approximately $N_\nu = 1.5$, in reasonable agreement with the corresponding value 3.2 from Table 1, while for the spectrum $F^1_\nu(E)$ from Ref. [33] this number is about 0.5, which already indicates a significant discrepancy with the LSD experiment (see number 5 in Table 1).

Unfortunately, a further comparison of the characteristic times of the theoretical neutrino signal (about 0.3 s) with findings in Refs [33, 41] reveals poor agreement with the experiment (about 7 s) [14]. Nevertheless, one can hope that the characteristic time of the expected neutrino signal in the future three-dimensional hydrodynamic calculations of the collapsar can be increased due to hydrodynamic timescales of the dynamic instability. Such an increase, for example, was already obtained in a spherically symmetric model of the collapse [23]: the characteristic time, which was determined by the accretion time of the 'neutrino–neutron' star formation, was found to be several seconds.

Table 1, in fact, demonstrates a satisfactory agreement between the results of the rotating collapsar model and experimental data on the first neutrino signal from SN 1987A. It is important to note here that the 'standard' model has strongly contradicted these data from the very first attempts at its theoretical interpretation [3].

Table 1. Number of events on detectors for the first neutrino signal from SN 1987A.

Detector	Registration threshold	Estimated number of interactions		Estimated number of events $N_1\,\eta$	Experiment 23.02.1987
		N_1	N_2		
LSD	5–7	5.7	4.9	3.2	5
KII	7–14	3.1	2.5	2.7	2
BUST	10	5.2		~ 1	1

2.2 Formation and evolution of a binary neutron star system under the action of gravitational radiation and mass exchange between the components

Thus, below we shall also assume that the nonlinear development of dynamic instability for the principal quadrupole azimuthal ($m = 2$) mode leads in the simplest case to the formation of a binary system of neutron stars accompanying the fragmentation of a rotating collapsar. During the fragmentation, the total mass of the system M_0 can be considered constant. The total angular momentum J_0 and energy can generally change, for example, due to the formation of a low-mass gas ejecta. Under the given parameters M_0 and J_0, it is easy to determine all the main parameters of the binary system [25, 26], assuming additionally that the system's orbits are circular. The obtained solution of this elementary celestial mechanics problem with the Newtonian treatment of gravitational interaction between components has one free parameter — the mass ratio of the low-mass component M_1 to the total mass of the system M_0: $\delta_0 = M_1/(M_1 + M_2) = M_1/M_0 \leqslant 1/2$.

In a more general case of elliptical orbits, the solution contains an additional free parameter — the initial orbital eccentricity e_0. However, a further consideration of the evolution of such an eccentric binary system under the action of gravitational radiation [34] showed that the eccentricity $e \leqslant e_0$ so rapidly decreases with time (in contrast to the constant quantity δ_0) that only circular orbits can be considered in the evolutionary problem. Notice that our studies are based on the remarkable analytical results by Peters and Mathews [45, 46], which also take into account only the loss of orbital energy and angular momentum of the binary system due to the emission of gravitational waves, when tracing the evolution of the system.

Thus, in the case of circular orbits a very simple formula for the characteristic time of the binary system evolution (in seconds) may be applied [34]:

$$t_{\text{grav}} = 2.94 \times 10^{-4} \, \frac{j_0^8}{m_0^{15} \delta_0^9 (1 - \delta_0)^9} \, . \tag{2}$$

The generalization of formula (2) to eccentric orbits was given in Ref. [34]. The eccentricity effect is then described by an additional factor $\tau(e_0) \geqslant 1$ on the right side of Eqn (2), and it plays a noticeable role only for ultimately eccentric orbits with $e_0 \to 1$. Formula (2) also contains dimensionless parameters $j_0 = J_0/(8.81 \times 10^{49}$ erg s) and $m_0 = M_0/2M_\odot$ (the denominators of these parameters contain the characteristic values of J_0 and M_0 in rotating collapsars). The quantity t_{grav} in formula (2) is formally defined as the characteristic time of the evolution of the binary system until final merging of its components, since in this solution of the celestial mechanics problem both neutron stars are considered as point-like masses.

Actually, the components of the binary system have, of course, nonzero radii, and at some finite orbital radius, which is directly related in astrophysics to the Roche lobe radius [47], the mass exchange between the components begins, in which the less massive neutron star M_1 becomes the donor for the more massive component, so that the ratio parameter δ decreases, becoming time-dependent function $\delta = \delta(t) < \delta_0$. The phenomenon of mass loss by the low-mass component in close (!) binary systems is the general feature of degenerate stars whose radius increases with decreasing mass of the star (in reality, these objects also include white dwarfs in addition to neutron stars!). Using papers by Paczyński et al. [48, 49] (other basic studies on the theory of binary star evolution can be found in books [50, 51]), we have managed to construct an analytical theory of the mixed evolution regime for a close binary system of neutron stars in which both gravitational wave emission and mass exchange between the components were taken into account [37]. This theory first of all implies that the difference between the characteristic time of evolution and that calculated using formula (2) is insignificant.

Therefore, we think it is quite natural to argue that the time of evolution of the binary system of neutron stars is almost fully determined by energy loss due to the emission of gravitational waves as long as two stars approach each other under the action of a gravitational radiation. We stress that all other factors, including the mass exchange between the components at the end of the evolution, play a secondary role. From the point of view of the intensity of emission of gravitational waves, the considered binary system is undoubtedly one of the most powerful sources of gravitational waves even in the typical case (see below) of low parameters δ_0 [36]. In connection with SN 1987A, as early as in paper [34] it was assumed, and later in paper [13] justified in detail, that the time interval between two neutrino signals from this supernova explosion can be identified with time t_{grav} from formula (2). In Table 2 we present some estimates of the parameter δ_0 for $t_{\text{grav}} = 16{,}920$ s, taken from paper [13], by assuming $m_0 = 0.9$ in formula (2) and slightly varying the parameter J_0. The second row of Table 2 is given for the smaller value of the parameter $j_0 = 0.7$, while the first row was calculated using $j_0 = 1.0$. Physically, such a decrease can reflect, in particular, an incomplete transfer of the angular momentum of the iron core into the orbital angular momentum of the binary system. It is seen from Table 2 that the sought value of δ_0 and the corresponding mass of the low-mass component M_1 is fairly small, but still exceeds the well-known lower limit of the neutron star masses near $0.1 M_\odot$ [52]. Thus, the low-mass component from Table 2 can be a neutron star. This applies even more so to the more massive component, so the necessary physical condition of fragmentation of the rotating collapsar into two neutron stars is satisfied. As was argued in Ref. [13], smaller values of δ_0 are more appropriate for accomplishing the hydrodynamic fragmentation than δ_0 close to 0.5 (in the last case, incidentally, the coalescence time is comparatively too small: $t_{\text{grav}} \approx 400$ s).

Table 2. The characteristic theoretical parameters of the binary system of neutron stars for SN 1987A (with the total mass $M_0 = 1.8 M_\odot$).

J_0, erg s	δ_0	$M_1/M_\odot$	J_{ac}/J_0	J_{ac}, erg s	Δt_{ac}, s
8.81×10^{49}	0.206	0.37	0.195	1.72×10^{49}	~ 0.9
6.17×10^{49}	0.139	0.25	0.235	1.45×10^{49}	~ 1.0

But the most important point in Table 2 is the notable decrease in the angular momentum during the evolution of the binary system: the fourth column gives the values of the angular momentum J_{ac} at the instant of time when the mass exchange begins, which are 4–5 times smaller than the initial angular momentum J_0. It turns out that exactly this decrease makes the effect of centrifugal forces insignificant during the collapse. In paper [20], a simple energy estimate was made, which showed that the total rotational energy indeed becomes small relative to the total gravitational energy in the rotating collapsar, with a similar decrease in the total angular momentum. Still earlier, of course, the criterion of dynamic instability in the rotating collapsar ceases to be met. Then, rotational effects can no longer prevent the revival of collapse of the more massive component. That is why it becomes possible to describe the appearance of the second neutrino signal from SN 1987A in the framework of the 'standard' model, but with some reservations (see Section 2.3).

The last column of Table 2 gives the time interval Δt_{ac} of the mixed evolution regime, which sometimes is referred to as the accretion regime, since the more massive component accretes all mass that was lost by the less massive star. Above we have already mentioned our paper [37] that provides a qualitative analysis of the differential equations describing the mixed regime, which take into account the dependence on the parameters j_0 and m_0. Paper [37] justifies the assumptions of the quasistationary character of circular orbits, the Newtonian approximation for the gravitational field, and some other conditions which are put into these equations (see also the final paper [53]). In particular, the necessary condition for the mass exchange (overrunning the Roche lobe radius by the low-mass component radius) was shown to be realized for different masses of this component down to about its critical value ($\delta \approx 0.1$, while by definition the critical value is $\delta_{\rm cr} = 0.055$). Unfortunately, in this narrow region, strictly speaking, it would be desirable to numerically solve the hydrodynamic problem of the mass exchange process until reaching the critical conditions [37]. The characteristic times of the mixed evolution regime shown in Table 2 are given exactly up to this problematic environment, but it is important that $\Delta t_{\rm ac} \ll t_{\rm grav}$ (the symbol $\sim$ in Table 2 reflects exactly the above inapplicability of the theory in this narrow environment).

Before describing the last stage in the rotational mechanism of core-collapse supernova explosions, we emphasize the huge difference in the time interval between neutrino signals from SN 1987A and the characteristic hydrodynamic times of neutron star formation: almost four orders of magnitude! The latter time scale can be derived from the time spread of the neutrino events in each signal: according to experimental data, this time spread is roughly 10 s. One can, apparently, recognize that the possibility of theoretical interpretation of this big distinction is an important advantage of the rotational scenario in comparison to the 'standard' model. In this respect one can also mention another possible explosion mechanism, namely, the magneto-rotational one, first proposed long ago by Bisnovatyi-Kogan [54] and elaborated in detail in a series of axially symmetric magneto-hydrodynamic (MHD) models described in review [55]. This mechanism, of course, should be considered as a serious theoretical alternative to the rotational scenario considered here. Future observations of core-collapse supernovae should decide which of the mechanisms is true. Nevertheless, the magneto-rotational mechanism has not provided a successful explanation for the double neutrino signal from SN 1987A. In addition, the mechanism requires a sufficiently rapid initial rotation of the stellar core to produce a huge toroidal magnetic field from the initial (dipole-like, in particular) field. The assignment of large initial rotation in this mechanism has much in common with our rotational scenario.

Another astrophysical problem apparently requires additional discussion. In line with the known famous double neutron star binaries (binary pulsars), we proposed, in fact, above that there can be 'short-living' binary systems of neutron stars with rather large mass ratios and the total mass not exceeding the upper limit for iron stellar cores. If the lower limit of the iron stellar core masses in relation to their collapse is thought to be close to the Chandrasekhar mass $1.2M_\odot$, the upper limit is poorly determined. In particular, the latter can be inferred to be about $2M_\odot$ from calculations of the late stages of the evolution of single massive stars. In paper [56], this upper limit was indeed obtained for a $25M_\odot$ star to be $1.85M_\odot$ (here we consider the baryonic mass of iron stellar cores), which could be considered satisfactory. However, it is quite clear that such an upper limit is additionally determined by theoretical studies of the SN 1987A phenomenon [5, 57]. It should be noted that paper [56] was also published after the SN 1987A explosion. An earlier analysis of these mass limits can be found in our old review [58], where somewhat different values were justified. But in the last review [59] we already used the limits quoted above and considered them as commonly accepted. Apparently, the most interesting in the described scenarios is the presence of a low-mass neutron star within the mass range (0.2–0.4) $M_\odot$, which according to Table 2 (virtually in the vicinity of the critical lower mass limit of neutron stars, $0.1M_\odot$) has not so far been found in nature.

One can hope that the rotational scenario of the core-collapse supernova explosion presented here will stimulate difficult searches for such low-mass neutron stars. The assumed existence of a binary system of neutron stars in the time interval between two neutrino signals from SN 1987A seems to be indirectly supported by the exhibition of unusual activity in detecting some enigmatic events by the LSD. Such events were recently attracted attention in Ref. [60]. Interestingly, a similar group of events was also detected within one hour before and after the first neutrino signal.

2.3 Orbital explosion of a low-mass neutron star with the critical mass — the explosion energy source of a collapsing supernova. The associated gravitational wave emission

In our paper [31], as well as in a series of papers [61–63], a one-dimensional hydrodynamic model was formulated and numerically calculated, thus showing that a neutron star with a critical mass close to $0.1M_\odot$ is destroyed in a nuclear explosion. In this explosion, neutrons experience fusion into atomic nuclei of the iron group elements via a grandiose chain of beta-processes. The most important result of the numerical calculations consists in the stable value of an ultimate energy release of 4.7 MeV per nucleon [31]. Notice that the total energy of neutron fusion into iron atomic nuclei reaches 9.155 MeV per nucleon, so that in the models described about half this energy is spent to overcome the gravitational field of such a star.

A shortcoming of the cited paper might be a simplified equation of state of matter, used in the calculations, which in fact neglected all the complex kinetics of beta-processes, i.e., the characteristic times of these nuclear reactions were artificially set to zero. But taking into account nonzero times, which is extremely complicated, especially for short-living atomic nuclei, apparently cannot prevent the explosive character of the nuclear synthesis [64], which, incidentally, is accompanied by an energy release comparable to the energy released during the entire thermonuclear evolution of the matter of normal stars (from hydrogen to iron). It is easy to check that the total energy release of neutron fusion in the nuclear explosion slightly exceeds 10^{51} erg, i.e., is remarkably close to the observed energy of supernova explosions (see Section 3).

The rotational scenario assumes that exactly such an explosion is produced by the low-mass neutron star orbiting the more massive component, when its mass is reduced to the critical value during the mass exchange process (Fig. 2). In paper [32], a numerical model of the debris expansion dynamics of the exploded neutron star was constructed, which is mainly determined by the strong gravitational field of the more massive neutron star. Clearly, this explosion is intrinsically three-dimensional, and an iron ejecta results from the explosion (see Fig. 2). For brevity, the massive component of the late binary system will be referred to as a pulsar, since this component, according to the scenario, must become subsequently the stellar remnant of the supernova outburst. In paper [32], the numerical model was calculated using the particle dynamics simulation (PDS) method known in plasma physics, but in this model the debris expansion dynamics was determined not by the electromagnetic fields of

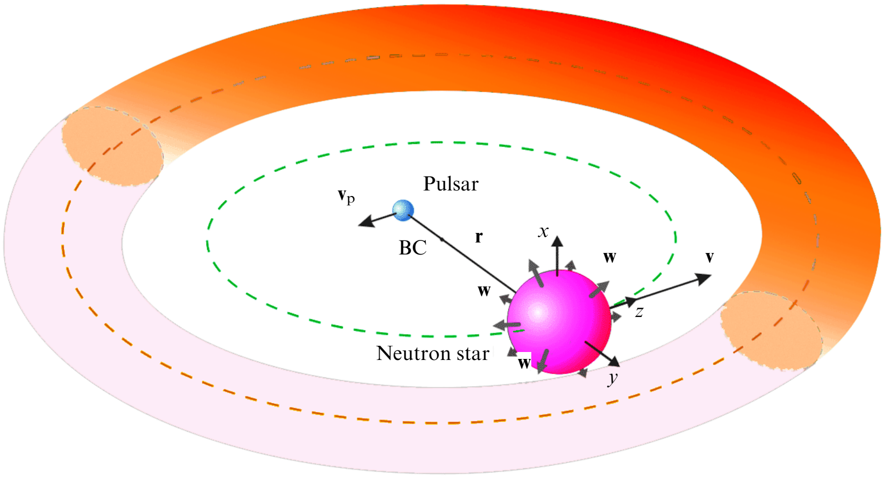

Figure 2. Schematic of the explosion of low-mass neutron star orbiting in double neutron star binary [32]. The three-dimensional explosion is considered in the Cartesian coordinates with the x-axis perpendicular to the orbital plane yz, the y-axis directed along the radius vector $\mathbf{r}$ from the massive component (pulsar) to the low-mass neutron star, and the z-axis directed along the orbital velocity vector $\mathbf{v}$ of the low-mass neutron star. $\mathbf{v}_\mathrm{p}$ is the pulsar's orbital velocity (BC is the barycenter of the binary system). The thick straight arrows (the vector $\mathbf{w}$) show the space-isotropic expansion velocity constant in modulus of the iron ejecta (the result of the neutron fusion into iron atomic nuclei). Shown is the toroidal iron atmosphere surrounding the binary star orbit. This atmosphere was formed long before the explosion (about 5 h) of the orbiting low-mass neuron star [70]. The atmosphere is coaxial with the orbit of the double neutron star binary and serves as a 'target' for the iron ejecta that carries the kinetic energy of the supernova explosion. Both objects (the iron ejecta and the toroidal iron atmosphere) have similar masses of around $0.1M_\odot$.

the plasma but by the gravitational field of the pulsar. The motion of the pulsar, in turn, was affected by the expanding ejecta of the exploded star, so its trajectory was appreciably different from the initial circular orbit. The model totally ignored the pressure effects in the ejecta, and a specific energy release of 4.7 MeV per nucleon constant over the entire mass was taken as the initial condition. We stress that this condition was determined at the stage of free expansion of the hydrodynamic model of the explosion of a low-mass neutron star with the mass $0.1M_\odot$ in paper [31]. In addition, the orbital velocity of the pulsar was assumed to be 1000 km s^{-1} and its mass was $1.8M_\odot$ in the initial conditions for the numerical model from Ref. [32]. Note that this velocity is quite typical for young pulsars. All above values fully determined the necessary initial conditions in the PDS model. The sufficient number of particles did not exceed 10^5 (not a big number in modern widespread PDS models).

It is quite natural that all particles separated in the course of time into two groups: 'hyperbolical' ones with the positive energy, and 'elliptical' ones with the negative energy. Notice that these groups are implied but not shown in Fig. 2. The elliptical particles form a sort of steady-form cloud around the pulsar after the pulsar significantly changes its velocity vector, having exchanged momentum with all macroparticles (the law of conservation of the total momentum, which is clearly zero in the circular orbit, is satisfied in the PDS model). As for the hyperbolical particles, they gradually dispersed in space in the form of iron ejecta similar to a moving spherical shell. It is this shell that carries the kinetic energy of the supernova explosion. It should be stressed that the numerical PDS model in Ref. [32] was tested by detailed comparison with an analytical solution for a purely Coulomb field of a point fixed source [65]. Earlier, the possibility of using this analytical solution in the problem of interest was pointed out by the authors of paper [66], who determined inter alia the amplitude of the total momentum of the ejecta formed by the exploded neutron star (see Ref. [67] for a discussion of the conserved Runge–Lenz vector in this problem). The recent paper [68] considered in detail the variation of all parameters of the problem, including the pulsar mass and velocity, and obtained solutions with the common noninstantaneous and inhomogeneous distribution of the explosion energy release. In Table 3 taken from Ref. [68] we present the values of the most important quantity — the total kinetic energy of the explosion for quite long time intervals, when the contribution of the gravitational energy can already be neglected (in fact, for time intervals exceeding 0.1 s). Table 3 lists, in addition to the kinetic energy E_exp of the explosion, four important characteristics for all variants of the model (M4, M6, M7, M8): (1) the mass ratio of the pulsar (M) to the exploded neutron star (m); (2) the initial orbital velocity V_po of the pulsar; (3) its velocity V_pf after interaction with the ejecta at the end of calculations, and (4) the fraction χ of the elliptical particles (all other particles are hyperbolical). It is seen that the initial velocity of the pulsar has the greatest effect on the explosion energy, and, apparently unexpectedly, the energy appreciably decreases for enhanced velocities (M8), since in this case the total angular momentum J_0

Table 3. The results of a three-dimensional numerical solution to the problem of explosion and expansion of a low-mass neutron star in orbit.

Model* / Parameters and results	M4	M7	M8	M6
M/m	18	18	18	12
V_po, 10^3 km s^{-1}	1	0.5	1.5	1
E_exp, 10^{51} erg	0.67	0.76	0.45	0.77
V_pf, 10^3 km s^{-1}	0.56	0.48	0.39	0.85
χ	0.23	0.03	0.36	0.09

* All four models have the same initial distributions of the energy release from neutron fusion into iron atomic nuclei with the characteristic time and space parameters ($\Delta t_\mathrm{exp}^{(0)} = 0.04$ s and function $w(r)$ from Ref. [68]).

decreases. The decrease in this parameter (V_{po}) causes only a decrease by an order of magnitude in the quantity χ (M7). The parameter χ also decreases with decreasing a mass ratio (M6). Generally, the variant M4, which was taken as the basic model in calculations [68], seems to be optimal, being apparently the most adequate in the case of SN 1987A. Nevertheless, in general the dependence of final calculated results on the parameters of the problem, including two parameters from Table 3 (M/m and V_{po}), appears to be rather moderate, which evidences the typical case of the basic model variant M4 and justifies the conclusions arrived at Ref. [32], in which exactly this model was considered.

Taking into account the importance of the values of the kinetic energy E_{exp} of the ejecta given in Table 3, we present the analytical expression for this quantity obtained in our paper [32] using the above law of conservation of the Runge-Lenz vector. This expression is especially useful with regard to the dependence on two characteristic dimensionless parameters of the problem:

$$v = \left(\frac{M}{m+M}\right)^{1/2}, \quad w = \frac{(2\varepsilon_0/m_0)^{1/2}}{(GM/a)^{1/2}}, \tag{3}$$

with $\varepsilon_0 = 4.7$ MeV and $a = GM^2/(m+M)\,V_{po}^2$, where a is the circular orbit radius or, more precisely, the distance between the components of the binary stellar system according to Kepler's law, and ε_0 is the value of the energy release per nucleon in the nuclear fusion of neutrons we discussed above. Then a very simple analytical expression for the energy E_{exp} can be obtained:

$$E_{exp} = \begin{cases} \dfrac{m}{2}\left(\dfrac{GM}{a}\right)(v^2 + w^2 - 2), & w \geqslant \sqrt{2} + v, \\ \dfrac{m}{16wv}\left(\dfrac{GM}{a}\right)\left[(v+w)^2 - 2\right]^2, & \sqrt{2} - v \leqslant w \leqslant \sqrt{2} + v, \\ 0, & w < \sqrt{2} - v. \end{cases} \tag{4}$$

The bottom row in formula (4) means the total capture of the ejecta by the gravitational field of the pulsar ($\chi = 1$), and the upper row, in contrast, corresponds to the absence of any capture ($\chi = 0$). The middle row signifies the intermediate case of the partial capture. For realistic values of the parameters v and w from formula (3), for example, $w = 1.62$ and $v = 0.973$ (for $M/m = 18$, $V_{po} = 1000$ km s^{-1}, and $m = 0.1M_{\odot}$), we get $a = 6.98 \times 10^2$ km and $E_{exp} = 0.61 \times 10^{51}$ erg. The last magnitude does not greatly differ from the value of E_{exp} shown in the first column of Table 3, which is equal to 0.67×10^{51} erg. Let us recall that the analytical expression exhibits the asymptotic character for $(m/M) \to 0$ [32].

Thus, in most calculations (with guaranteed accuracy control) the energy E_{exp} is very close to the characteristic value of 10^{51} erg. Of course, the release of this energy stored in the ejecta according to the collisionless PDS model occurs when the ejecta collides with the nearby inner layers of the presupernova envelope. Only then does the hydrodynamic stage of the explosion generating a powerful shock wave begin. In fact, the ejecta can collide with the so-called toroidal atmosphere which forms before the explosion of the orbiting low-mass neutron star at a time close to the instants of the first collapse and the formation of the rotating collapsar [69, 70]. Remarkably, such an atmosphere is not only stationary [69] but also stable with respect to different hydrodynamic disturbances [70], including those in which theoretical stability criterions are met [38]. In short, it can 'wait' the entire time of the existence of the double neutron star binary until the collision with the ejecta from hyperbolical particles. The toroidal atmosphere consists of matter from outer layers of the iron stellar core and the external silicon layer [70] in which the initial structure of the presupernova is taken from reliable evolutionary models [71].

As for the elliptical particles, they, as we already said, persistently accompany the pulsar moving asymptotically along a straight line with the velocity reduced by 30–50% relative to the initial one [68]. Quite unexpectedly, numerical calculations [32] revealed that a sizable fraction of the elliptical particles are found in orbits with sufficiently large eccentricities: around 20% of the particles from the vicinity of the pulsar, i.e., in the perigee of their orbits, have high kinetic energies of several GeV per iron nucleus (incidentally, these characteristic energies can also be obtained using the analytical solution mentioned above). Clearly, in nuclear interactions of such particles with iron atomic nuclei around the pulsar (for example, in the accretion disc) can generate pions and, hence, muonic neutrinos with an energy of about 100 MeV. Presently, one can only guess what effect such particles could have on the properties of the second neutrino signal from SN 1987A.

But the main properties of this neutrino signal are due to the revival of the collapse process in the more massive neutron star which has had time to accrete the mass lost by the low-mass companion before its explosion in orbit. It should be remembered that all studies of the evolution of close binary systems, including our papers [37, 53], justifiably assume a conservative approach to mass transfer with the accretion of all mass by the more massive star, so that the renewed collapse occurs in the star with the mass $M_2^* = M_0 - 0.1M_{\odot}$, i.e., almost equal to the initial iron core mass M_0. Notice that the collapse revival is also facilitated by the loss of the proper angular momentum of the pulsar, which was preserved from the fragmentation but exhausted according to the law of corotation in the stage of a close binary system [26, 50]. Unfortunately, the last effect has not so far been estimated quantitatively. We repeat that the revival of the collapse seems to be very likely. This stage of the collapse is basically similar to that studied in the 'standard' model.

Calculations of the hydrodynamic models of explosion were started by us using the two-dimensional (axially symmetric) approximation in paper [30], although only the three-dimensional formation of the ejecta from the hyperbolical particles and its collision with the toroidal atmosphere discussed above should be considered as adequate. In this paper, the nuclear energy release in the exploded neutron star was artificially 'smeared out' over its circular orbit which by definition is coaxial with the toroidal atmosphere on retention of the orbital velocity (see Fig. 2). Both these toroidal shells had approximately the same mass of $0.1M_{\odot}$ (see Ref. [70]). Next, the gravitational interaction from all three sources was taken into account since, besides two toroidal shells, it was determined by the central point-like source (the pulsar with a mass of $1.8M_{\odot}$). The hydrodynamic calculations were carried out until the shock wave front propagated up to a rather large mean radius on the order of the initial radius of the iron stellar core (about 10^9 cm). The integral (over time) energy flux through the spherical surface with such a radius was about 0.2×10^{51} erg. This is a comparatively low value for the total supernova explosion energy. Nevertheless, it can be treated as quite promising, because it must be considered as the lower bound of the total energy. In the adequate three-dimensional approximation, which soon will be available as the next step after the three-dimensional modeling of the above-described expansion of a neutron star exploded in orbit [32, 68], we can anticipate a substantial increase in the resulting total energy of the explosion. This is supported, in particular, by such calculations performed in Refs [27, 28, 72] (see also their critical discussion in work [30]), in which the natural spherical form of the ejecta from the exploded neutron star in orbit was assumed. Let us recall that these calculations were also carried out in the axially symmetric hydrodynamic approximation, but their differential schemes were constructed using two totally independent approaches (the usual Godunov method in Eulerian coordinates, and a mixed Euler–Lagrange method [73] which is essentially more precise).

The rotational scenario of the core-collapse supernova explosion certainly assumes the presence of a pulsar in the supernova remnant or, more precisely, a hot neutron star with mass $M \leqslant 2M_{\odot}$ moving with a high velocity V_{p} of several hundred kilometers per second, up to $V_{\mathrm{p}} \approx 1000$ km s^{-1}. Of course, there is the separate problem of the presence of a significant magnetic field and the nonzero angle between the rotation axis of the neutron star and its magnetic dipole vector [74] in order for the neutron star to be observed as a pulsar from the very beginning. But is there the possibility of merely registering the newborn neutron star as a point-like X-ray source in the supernova remnant of SN 1987A only twenty years after the outburst? These possibilities were carefully studied in paper [75]. So far, no such source has been discovered in this very young supernova remnant. Theoretical models of the cooling of very hot neutron stars have not to date been elaborated adequately with full account of the complex physics of their interiors, first and foremost the superfluidity effects of protons and particularly dominating neutrons. Nevertheless, it cannot be ruled out that the stellar remnant in SN 1987A can be hidden from existing X-ray and gamma-ray telescopes (for example, the INTEGRAL observatory currently in orbit) by gas-dust debris of the supernova explosion. It is important, however, that the optical depth of these clouds not be very high (about 10 dimensionless units according to the cited paper). So there is hope that this opaque expanding medium will be dispersed sooner than the born hot neutron star, with a rather high expected mass of about $2M_{\odot}$, cools down. Then a rare opportunity will appear to observe the 'hot' neutron star still before the so-called temperature relaxation in its interiors begins [75]. This relaxation in general causes a very sharp decrease in the X-ray luminosity of neutron stars with any mass, but the higher the mass the sooner it starts. In the case of SN 1987A there are compelling arguments in favor of a high initial mass of the collapsing iron core ($M \approx 1.8M_{\odot}$ in the above consideration) and, hence, of the central neutron star in the outburst stellar remnant. Of course, there is a very low probability that a rotating black hole and not the rotating collapsar was formed in the explosion. But then it would be hard to theoretically explain the very remarkable observation of two neutrino signals from the explosion, especially the first of them. It is arduous to imagine, in particular, the fragmentation of a rotating black hole. It would be rather expected that a black hole could result from the renewed collapse of the more massive component of the double neutron star binary, so a nonrotating black hole would appear in the supernova SN 1987A remnant instead of a pulsar. However, the probability of this occurring seems to be quite low.

Unfortunately, it has not yet been managed to theoretically interpret a distinct signal detected by the gravitational-wave antenna in Rome [76–78] and correlated with the first neutrino signal. The sensitivity of the antenna was assumed to be 10^{-18} (the dimensionless parameter h for metric perturbation near the detector [79]). In our paper [36] cited above (see Section 2.2), the gravitational radiation from a short-living binary neutron star system was solved, including the parameters appropriate for SN 1987A. Our calculations definitely conclude that it is impossible to detect gravitational waves from the same neutron star binary during the time interval around the instant of appearing the second neutrino signal from SN 1987A, which indeed was the case for the Rome antenna. Nevertheless, at the instant of time of the first neutrino signal when (according to the rotational scenario) the fragmentation of the rotating collapsar occurred [25], no quantitative estimates of the associated gravitational wave emission were obtained in Ref. [36]. But qualitative physical considerations made in that paper suggest that the high power of the observed gravitational radiation (with a maximum gravitational wave emission power of $c^5/G \approx 3\times10^{59}$ erg s^{-1}) could be sufficient to reach the high value of the parameter h mentioned above, so the experimental data [76–78] will thus get theoretical support. In this case, the total energy of the gravitational radiation from SN 1987A, obtained in Ref. [36], is around 10^{52} erg within the small time interval close to the second neutrino signal, while in Ref. [80] almost the same value of 3×10^{51} erg was obtained in the vicinity of the first neutrino signal. Thus, we should hope for future theoretical calculations of the gravitational wave emission during the fragmentation of the rotating collapsar.

Here, one more point discussed in paper [36] should be taken into account. In principle, in exploding a low-mass neutron star in the rotational scenario there is an alternative variant of its early coalescence (i.e., before reaching the critical mass $0.1M_{\odot}$) with the more massive component. Such a process has actively been discussed in the literature as one of the most powerful sources of gravitational wave emission in nature, but for two equal-mass neutron stars $1.4M_{\odot}$ in size, the value which is the most common in pulsar studies [74]. In the hypothetical neutron star binary considered above, the total mass of coalescing neutron stars is appreciably smaller: $M_0 \leqslant 2M_{\odot}$. Despite the power of the gravitational radiation associated with this coalescing binary neutron star being smaller than that during the coalescence of a neutron star binary with the total mass $M \approx 2.8M_{\odot}$, a significant second (?) power peak can appear, of course, at the final stage of the binary system coalescence, during the mass transfer process between the binary components [36]. In the cited paper it was reliably shown that without coalescing, i.e., during the explosion of the low-mass neutron star in orbit, no second (!) maximum appears, and only one maximum is generated at the end of the early stage of the approaching of the components without mass transfer. In contrast, all characteristic 'light curves' in Ref. [36] display a very moderate power at the instant of explosive energy release. Thus, future gravitational wave signals [81] can ultimately solve this alternative in favor of the rotating mechanism of core-collapse supernova explosions if 'light curves' with one maximum near the second neutrino signal or, in other words, at the instant of time of the supernova explosion energy release, are detected. On the other hand, the detection of a 'light curve' with two maxima separated by a small time interval (on the order of one second!) will apparently support the model of coalescence of two neutron stars. But then, how can one explain an energy release of order 10^{51} erg? In other words, the reason for the core-collapse supernova explosion in this case will again become the puzzle of the 21st century... .

3. Conclusions

The well-known fact that the total energy release in the explosion of supernovae of all types is very close to 10^{51} erg appears to be very surprising. In review [59] we infer the energy interval of $(0.5–2.0) \times 10^{51}$ erg from the many-year analysis of observational data for more than one thousand supernova outbursts. Type II supernovae (when strong hydrogen lines are present in their spectra, according to the commonly accepted classification of supernovae of type I and type II) are most numerous: $\sim 90\%$ of the total number (see review [59] and references cited therein). To determine the total energy release in an explosion, the method of light curve and spectral fitting by numerical hydrodynamical modeling of presupernova envelopes is widely used. The initial structure of these envelopes is deduced from the theory of late stages of stellar evolution or simply by constructing here initial models of these stars in hydrostatic equilibrium.

According to the modern physical classification, all supernovae are also divided into two classes — collapsing and thermonuclear supernovae [59]. The core-collapse supernovae are thought to almost fully represent all observed type II supernovae and some fraction of type I supernovae. The presupernovae of these objects comprise sufficiently massive stars with a mass of more than $10M_{\odot}$, in which central iron cores are formed during evolution. It should be noted that hydrodynamic models of the explosion of envelopes, whose development already started about half a century ago [82], are the natural continuation of classical hydrostatically equilibrium models of the structure and evolution of stars [83, 84], in that they were also spherically symmetric but without hydrostatic equilibrium. The one-dimensional theory of explosion of presupernova shells, whose models of explosion were discussed above, is distinguished by assuming that the explosion is instantaneous and concentrated near the presupernova center, and the initial conditions of the theory include only the value of the total energy release in an explosion as the free parameter of the problem. Thus, the full hydrodynamic problem of the collapse and explosion of a supernova is separated into two problems related to each other by this initial parameter alone [58]. The first problem, which is dedicated to the physical explanation of the supernova explosion mechanism, was considered in Sections 1 and 2 of this review (only collapsing supernovae were considered, however).

In each particular case of supernova explosion, the numerical solution of the second problem is used to evaluate the total energy release at which theoretical photometric light curves (in the traditional spectral ranges U, B, V, R, I, etc.) best fit the observed ones, including those from the nearby SN 1987A [85, 86]. In the last case, the comparison with some spectral lines, hydrogen H_{α} first of all, was found fruitful [87].

It is by this means that the total energy release we are interesting in was determined to be very close to 10^{51} erg. It should be noted that Stan Woosley proposed calling this value Bethe, after the great astrophysicist Hans Bethe. Bethe himself referred to this value as 'foe' (i.e., an enemy) (see his famous review [88]). Quite recently it became possible to theoretically explain the explosion (the second problem!) of an unusually bright SN 2006gy almost retaining a total energy release on the order of one Bethe (2.9×10^{51} erg). This succeeded in spite of the maximum of the bolometric (integrated over the spectrum) light curve being observed to exceed those of the average type II supernovae by several dozen times (2×10^{44} erg s^{-1} vs. 8×10^{42} erg s^{-1}) [89, 90]. Clearly, there is no need to consider in detail other arguments supporting the existence of a surprisingly narrow energy interval of around 10^{51} erg for the total energy release in core-collapse supernova explosions. In the rotational scenario presented, most likely, this the more important feature of type II supernovae has a natural explanation as being the energy of explosion of a low-mass neutron star with mass close to the critical value $0.1M_{\odot}$ in orbit around a more massive neutron star. As for the scatter in the energy release values, it can be explained by very different reasons — from the idealization of real physical processes in the scenario to an inaccuracy in the determination of this value from observations.

In the Conclusions, problems of the rotational scenario to be solved should also be emphasized. In the presentation of this scenario given above, three stages of its development were pointed out. Naturally, they were considered in three consecutive Sections 2.1–2.3 of this review. In fact, the fourth stage [it would be the second stage in the scenario (?)] could also be separated — the fragmentation of the rotating collapsar. Clearly, at this stage all possible three-dimensional hydrodynamic models should be invoked, more specifically, to study the quadrupole mode of the dynamic instability development. It should be stressed that the similar problem of theoretical astrophysics exists in considering the initial stellar collapse in the star formation process with rotation. This problem is also extremely complicated and is far from being fully solved. Yet there are a lot of binary stars in nature...

Unfortunately, in the last two decades progress in solving this problem with the theory of core-collapse supernova explosions has turned out to be small as well, although some attempts have been made [80, 91, 92]. The authors of work [92] used the so-called simple compression model of some targets, developed in calculations of three-dimensional deformations of the shells of these targets with the realistic equations of state. In calculations with the equation of state for nuclear matter and with account for gravitation, the authors of Ref. [92] concluded that in such a primitive model the collapsing star is broken up into 'pieces' for a broad range of initial disturbances. This work, certainly, needs to be continued and further developed.

In similar calculations, in general, one should take into account a powerful gravitational wave emission with the local dependence on thermodynamic parameters. This was done in paper [80]. In particular, the total emission energy carried away by gravitational waves is 3×10^{51} erg, i.e., $\approx 1\%$ of the rest-mass energy of the collapsing star with mass $1.4M_{\odot}$, with the maximum power indeed occurring at the instants of culmination of the hydrodynamic process. It is important to note that this energy turned out to be of the same order as the kinetic energy of the fragmenting star, so indeed a self-consistent process takes place. Unfortunately, the calculations considered have not so far been seriously further developed and improved, which is undoubtedly very desirable (see Ref. [91]). In addition, these calculations did not lead to the star breaking up into parts and only demonstrated the formation of an ejecta with a high angular momentum. The rapid development of methods of three-dimensional hydrodynamic calculations recently (see Ref. [93]) has allowed us, however, to hope that in the nearest future the needed (difficult) modeling of the processes of fragmentation of collapsing and rotating stellar cores will be carried out. Nevertheless, we should stress that such a self-consistent estimation of gravitational radiation does not seem to be so important in the above-considered problem of the approach of the binary neutron star, resulting from the fragmentation in our rotational scenario (see Section 2.3). Indeed, in our calculations gravitational radiation was evaluated assuming point-like masses, which is justified almost up to the final stage of the binary approach (see Section 2.2). However, at the last, very short, stage of the neutron star approach (with the mass exchange) the point-like mass approximation breaks [37, 53], and three-dimensional hydrodynamic modeling is in order (see Section 2.2). Then, the self-consistent consideration of gravitational radiation can become significant.

Thus, it remains to hope that the progress in the numerical modeling of the three-dimensional hydrodynamic process of the rotating collapsar fragmentation will be ultimately achieved. One could probably be satisfied will the progress on the scale we have reached recently in solving another key problem, described in much detail in Section 2.3 — the problem of the explosion of a low-mass neutron star in orbit around a more massive companion surrounded by a toroidal iron atmosphere. At least the characteristic explosion energy of core-collapse supernovae on the order of one Bethe was justified in these calculations. The progress achieved in this final stage of the rotational scenario (the fourth with account for the second, unresolved, stage) would be, of course, impossible without experimental data on the neutrino emission from SN 1987A. Equally important experimental data for understanding the mechanism of core-collapse supernova explosions could be provided by detectors of gravitational waves. In particular, it would be desirable to understand what kind of a gravitational wave signal was registered from SN 1987A in Rome. It should be borne in mind that gravitational wave signals can actually be detected from huge distances on the order of 1 Mpc, and their sources are not distorted due to deposition effects, unlike neutrino signals. It is also important to continue careful searches for point-like X-ray sources in the supernova remnant of SN 1987A to find the stellar remnant of the explosion — a very young, very hot neutron star of high mass.

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