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Hydrodynamic processes of asymmetric collapsing supernovae explosion with rotation

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Hydrodynamic processes, by which the collapse of stellar core triggers the supernovae explosion, were studied in detail by numerical solution of axially symmetric problem taking into account fast initial rotation of iron core. Simulations showed the propagation of a strong diverging shock wave with a large asymmetry of explosion and with a total post-shock energy comparable to the characteristic energies of observed supernovae. Physical background for the formulation of the problems under consideration is the rotational explosion scenario for collapsing supernovae. According to this scenario supernovae explosion is preceded by the formation of a close binary system of neutron stars through the fragmentation of a rapidly rotating preneutron star. Such neutron star binary evolves to the point of explosion due to the losses of energy and angular momentum via the emission of gravitational waves in the presence of uniform or toroidal atmosphere - another residual of iron core collapse.

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1. Introduction

The mechanism of the core-collapse SNe is not yet understood in every detail. The most distinctive feature of these SNe is an enormous energy of $(3 \div 5) \cdot 10^{53} erg = (10 \div 15)\% M_{Fe} c^2$ radiated in form of neutrinos and antineutrinos of all the flavors (e; μ; τ), M_{Fe} is a mass of the iron core. One would think that it should not be a problem to extract less than 1% from the energy of a powerful neutrino flux to ensure the expulsion of the SNe envelope. However, an extensive hydrodynamical modeling during the last thirty years [12 - 18] has demonstrated that in case of spherical symmetry it is very hard (if possible at all) to simulate the explosion. Basing on this research, an empirical theorem can be formulated telling that spherically-symmetrical models do not result in expulsion of an envelope; the SN outburst does not occur: the envelope falls back on the collapsed core.

Among other models (*large-scale neutrino-driven convection, interaction between rotation and magnetic field*) proposed to describe non-spherical mechanism of the SN explosion there is a scenario of rotational fragmentation followed by a NS explosion. The key point for this scenario is the presence of rotation in the stellar core that is about to collapse. The mechanism of the SN explosion proposed in [1] is based on the rotational instability and develops through the following stages.

First, the rotational energy of the collapsing core E_{rot} reaches the limit of stability with respect to fragmentation: $E_{rot} / |E_g| > 0.27$ (E_g is the core gravitational energy) [2]. Then the core of mass M_0 fragments into a close binary system of proto-neutron stars of different masses M_1 and M_2 ($M_1 + M_2 = M_0$; assume $M_2 < M_1$ hereafter). These binary components begin to approach each other due to the loss of total angular momentum and kinetic energy of orbital motion through the radiation of gravitational waves [3]. The mutual approach of the components lasts until the orbital radius reaches a critical value for which the less massive component fills its Roche lobe. There begins a rapid mass transfer from the component M_2 to the component M_1. The mass M_2 is rapidly decreasing down to the minimum possible mass of a NS (~ 0.1 solar mass), when the process of the hydrodynamic destruction of a low-mass component begins. Such a dynamical instability is controlled by the rate of beta-processes, and initially is developing rather slowly. It terminates, however, with a short ($\sim 0.05 s$) phase of a violent transformation of the internal energy into kinetic energy and work against gravity. The resulting energy release is expected to be as large as $\sim 10^{51} erg$ (~ 4.8 MeV per nucleon) [4].

The weak point of the whole approach is the fragmentation process [24]. Formation of a light companion around a main body implies breaking of spherical and axial symmetry. During dynamical collapse, unstable bar modes can grow in a fluid that may end with fragmentation. However this is known to occur only if the core contracts almost isothermally [19], but collapse in type II supernovae is far from isothermal so that instabilities of this type do not have time to grow [20]. Rapid rotation in equilibrium bodies is known to excite non-axisymmetric dynamical instabilities. Core collapse simulations of unstable rotating iron cores [22] or polytropes [21] indicate that protoneutron stars, soon after formation, can rotate differentially above the dynamical stability limit. Strong nonlinear growth of the dominant bar-like deformation ($m = 2$) is seen in these cores. The bar evolves, producing two spiral arms that drain the core's excess angular momentum outwards. Another possibility refers to the case of fizzlers, temporary equilibrium bodies supported almost entirely by rotation, which are driven dynamically unstable against bar-like modes by deleptonization of hot nuclear matter on timescales of $\approx 1 \div 10 \sec$ [23], producing spiral patterns around a central core. In all these calculations however there is no sign of fission or fragmentation into separate condensations. However, according to Bonnell's picture [19], the evolution of the bar instability is more complex, in reality. If the rapidly spinning protoneutron star core or fizzler goes bar unstable when surrounded by a fallback disk, then matter present in the spiral arms interacts with this material. The sweeping of a spiral arm into fallback gas can gather sufficient matter to condense, by strong cooling and deleptonization, into fragments of neutronized matter. This occurs because the $m = 1$ mode grows during the development of the $m = 2$ mode. The $m = 1$ mode causes the off-centering of one spiral arm which then sweeps up more material on one side than the other during continuing accretion. The condensation may eventually collapse into a low mass protoneutron star fragment or in a few fragments of material. This has never been proved numerically.

The low-mass NS explosion model has no problems with the explanation of the explosion asymmetry (like that observed for SN1987A) and the origin of the high-velocity pulsars. There is no problem in this scenario also with dissociating of the heavy elements in the infalling envelope. The most impressive feature of the scenario is its ability to explain the two neutrino signals (LSD and KII, IMB) from SN1987A in the framework of a single self-consistent model. In the context of described model there were solved several hydrodynamical problems for various separated stages of the scenario.

2. Post-shock accretion

Two-dimensional axisymmetric hydrodynamic problem of the post-shock accretion is solved numerically. Simulation demonstrates the formation of a toroidal atmosphere during the collapse of an iron stellar core and outer stellar layers. Numerical model proves the stability of toroidal structure on hydrodynamic time scales.

2.1 Problem statement

The gravitational collapse of stellar iron cores is known to have led to a clear separation of the collapse into two stages. At the first stage, the inner part of the iron core with a mass M_{iFe} < $1M_{\odot}$ collapses homologically. As for the remaining outer part of the iron core, it remains almost in an initial state of hydrostatic equilibrium. This moment of time is assumed to be taken as the initial one ($t = 0$). An evolutionary model for the pre-SN [5] with a total mass of $25M_{\odot}$ is used as the initial data for the distribution of thermodynamic quantities in the outer shells of a massive star.

The considered problem is described by the equations of ideal fluid dynamics with assumption of axial symmetry (g_φ, $\partial/\partial\varphi = 0$). We use the equation of state for the matter which is assumed to be a mixture of a baryonic component (treated as an ideal gas of nuclei) that includes free nucleons (n, p), helium (^4He) and iron (^{56}Fe), an electron-positron gas with arbitrary degeneracy and relativity and blackbody radiation. The equation of state obeys the nuclear statistical equilibrium conditions with a constant ratio of the mass fractions of neutrons and protons, including those bound in the helium and iron nuclides, $\theta = 30/26$. The initial profiles [5] were corrected with the new equation of state and non-zero rotation in order to obtain hydrostatic equilibrium for initial state.

2.2 Results

The formation of a toroidal structure in the vicinity of a proto-neutron star obtained in the numerical simulation is considered to be the main result of the study [6]. This process prevents the accretion of the stellar envelope on the central compact object. It is very significant result for the scenario of rotational fragmentation followed by a low-mass neutron star explosion because of the presumed long existence of the close binary system of neutron stars (up to several hours). It should also be emphasized that the numerically calculated specific parameters of toroidal structure are largely determined by the form of the chosen initial rotation law for the inner presupernova layers (the outer part of the iron core and other shells). Nevertheless, the very formation of a toroidal atmosphere during post-shock accretion is a universal phenomenon that depends weakly on this circumstance.

The formulation of the problem on the formation of a toroidal structure was itself largely reinforced by the existence of analytical solution to the hydrostatic equilibrium equations for a cool iron gas in the gravitational field of a proto-neutron star [7]. Numerical solution, first, shows the stability of such configuration of matter against two-dimensional perturbations and, second, removes several restrictions in the formulation of the analytical problem [7] due to the allowance for non-zero matter temperature and the effect of self-gravitation.

3. Asymmetric explosion model

The explosion of a low-mass neutron star (in a close binary system) on a circular orbit in the presence of a rotating, hydrostatically equilibrium toroidal atmosphere has been modeled numerically [8]. Two-dimensional axisymmetric simulation shows the propagation of a strong divergent shock wave with a total energy of $\sim 0.2 \cdot 10^{51} erg$ at initial explosion energy release of $\sim 1.0 \cdot 10^{51} erg$. The mass of synthesized radioactive ^{56}Ni is estimated in the framework of explosive nucleosynthesis [9].

3.1 Introduction

According to the rotational scenario the neutron star binary formed through the fragmentation evolves due to the losses of energy and angular momentum via the emission of gravitational waves. And the orbit of the binary becomes circular by the time the low-mass companion fills its Roche lobe almost independently of the initial eccentricity of the binary system [10]. Thus the parameters of initial state for a binary are defined by Kepler's simple formulas. And the only parameter is the higher-mass component velocity, which is considered to be close to the known high kick velocities of young pulsars. So for this parameter is taken a reasonable value of $1000\,km/s$ [11].

A low-mass neutron star in assumed axisymmetric formulation of the problem is represented by an exploding torus ring. In established equation of state part of the internal energy of the matter is contained in the rest energy of the nuclei (if the iron mass fraction X_{Fe} is less than unity), so the choice of initial conditions in the region of energy release was treated very carefully in order to obtain right value for the internal energy of the explosion products (~ 4.7 MeV per nucleon).

3.2 Results

Instead of describing an exploding neutron star in the shape of a sphere, we had to specify it in the shape of a torus ring. It is qualitatively clear that this change in initial conditions excluded the possibility for the development of a directed asymmetry with the leading direction of the exploded neutron star velocity vector. In this model, the explosion is attributable only to energy release as the low-mass neutron star is destroyed. In this case, there is absolutely no contribution from the kinetic energy of the orbital motion of the exploding star. The orbital velocity becomes the rotational velocity of the torus introduced in the initial conditions for which the corresponding centrifugal force is exactly balanced by the attractive force of the pulsar placed at the coordinate origin. In this formulation of the problem, it was rigorously taken into account the gravitational interaction. Thus, it is quite clear that the final explosion energy as the total energy of the divergent shock wave that passed through the outer boundary of the computational region should be appreciably lower than it could be in a detailed 3D simulation of the same problem. Indeed, the final energy is $\sim 0.2 \cdot 10^{51} erg$, which is not far from the characteristic supernova explosion energy ($\sim 1.0 \cdot 10^{51} erg$), so it undoubtedly yields a considerable lower limit for the final explosion energy in the rotational scenario.

According to the simple reasoning behind explosive nucleosynthesis [9] it can be stated that in the pre-SN shells composed of α-particle nuclei, radioactive nickel is synthesized outside the iron core in very short hydrodynamic times when the nuclear statistical equilibrium conditions are established. The post-shock temperature drops below its critical value by a time of $t \approx 1.0 s$. So it is possible to give an estimation for the synthesized nickel mass, which is about ~ 0.020 $M_{\odot}$.

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