Magnetorotational Mechanism of Supernova Type II Explosion

S.G. Moiseenko[1], G.S. Bisnovatyi-Kogan[1], and N.V. Ardeljan[2]

[1] Space Research Institute, Profsoyuznaya str. 84/32 Moscow 117997, Russia; moiseenko@iki.rssi.ru, gkogan@iki.rssi.ru

[2] Department of Computational Mathematics and Cybernetics, Moscow State University, Vorobjevy Gory, Moscow B-234 Russia; ardel@cs.msu.su

Summary. Results of 2D simulations of the magnetorotational mechanism of supernova type II are presented. Amplification of toroidal magnetic field of the star due to differential rotation of the star leads to the transformation of the rotational (gravitational) energy to the energy of the supernova explosion. In our simulation the energy of the explosion is 1.12×10^{51} erg. The explosion ejects about 0.11 $M_{\odot}$.

1 Magnetorotational Mechanism

The magnotorotational supernova (MRS) explosion model was suggested in [5]. The idea of MRS consists of getting explosion energy from the rotational (gravitational) energy of the collapsed magnetized massive star. 1D numerical simulation of the MRS mechanism has been made in [1, 6]. We have made 2D numerical simulation of the MRS using specially developed implicit conservative Lagrangian scheme on triangular grid with grid reconstruction. Our results show that MRS leads to the energy output of the 1.12×10^{51} erg and ejection of 0.11 $M_{\odot}$.

Core collapse of a star leads to formation of the rapidly (almost rigidly) rotating neutron core and a differentially rotating large envelope. The explosion energy for the supernova is taken from the rotational (gravitational) energy of the magnetized star. The magnetic field plays the role of the “transmission belt” for the rotational (gravitational) energy to the energy of the supernova explosion. Toroidal component of the magnetic field is amplifying with time due to the differential rotation of the star. When the force produced by magnetic pressure substantially changes the local balance of forces a compression MHD wave appears and goes through the star's envelope outwards. Moving along a steeply decreasing density profile this wave transforms to the MHD shock which produces supernova explosion.

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2 Formulation of the Problem

2.1 Basic Equations

Consider a set of magnetohydrodynamical equations with self gravitation and with infinite conductivity:

$$\frac{\mathrm{d}\mathbf{x}}{\mathrm{d}t} = \mathbf{u}, \quad \frac{\mathrm{d}\rho}{\mathrm{d}t} + \rho \nabla \cdot \mathbf{u} = 0,$$

$$\rho \frac{\mathrm{d}\mathbf{u}}{\mathrm{d}t} = -\nabla \left(p + \frac{\mathbf{H} \cdot \mathbf{H}}{8\pi} \right) + \frac{\nabla \cdot (\mathbf{H} \otimes \mathbf{H})}{4\pi} - \rho \nabla \Phi,$$

$$\rho \frac{\mathrm{d}}{\mathrm{d}t} \left(\frac{\mathbf{H}}{\rho} \right) = \mathbf{H} \cdot \nabla \mathbf{u}, \quad \Delta \Phi = 4\pi G \rho,$$

$$\rho \frac{\mathrm{d}\varepsilon}{\mathrm{d}t} + p \nabla \cdot \mathbf{u} + \rho F(\rho, T) = 0,$$

where $\frac{\mathrm{d}}{\mathrm{d}t} = \frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla$ is the total time derivative, $\mathbf{x} = (r, \varphi, z)$, $\mathbf{u}$ is velocity vector, ρ is density, p is pressure, $\mathbf{H} = (H_r,\, H_\varphi,\, H_z)$ is magnetic field vector, Φ is gravitational potential, ε is internal energy, G is gravitational constant, $\mathbf{H} \otimes \mathbf{H}$ is tensor of rank 2, $F(\rho, T)$ is the rate of neutrino losses, other notations are standard..

Axial symmetry ($\frac{\partial}{\partial \varphi} = 0$) and symmetry to the equatorial plane ($z = 0$) are assumed.

2.2 Equations of State

The equations of state $P(\rho, T)$ [2]. includes approximation of the tables from [4, 8] for the cold degenerate matter $P_0(\rho)$: $P \equiv P(\rho, T) = P_0(\rho) + \rho \Re T + \frac{\sigma T^4}{3}$,

$$P_0(\rho) = \begin{cases} P_0^{(1)} = b_1 \rho^{1/3} / (1 + c_1 \rho^{1/3}), & at\ \rho \le \rho_1, \\ P_0^{(k)} = a \cdot 10^{b_k (\lg \rho - 8.419)^{c_k}} & at\ \rho_{k-1} \le \rho \le \rho_k,\ k = \overline{2,6} \end{cases} \tag{1}$$

$b_1 = 10.1240483$, $c_1 = 10^{-2.257}$, $\rho_1 = 10^{9.419}$, $b_2 = 1.0$, $c_2 = 1.1598$, $\rho_2 = 10^{11.5519}$, $b_3 = 2.5032$, $c_3 = 0.356293$, $\rho_3 = 10^{12.26939}$, $b_4 = 0.70401515$, $c_4 = 2.117802$, $\rho_4 = 10^{14.302}$, $b_5 = 0.16445926$, $c_5 = 1.237985$, $\rho_5 = 10^{15.0388}$, $b_6 = 0.86746415$, $c_6 = 1.237985$, $\rho_6 \gg \rho_5$, $a = 10^{26.1673.}$

Here ρ is a total mass-energy. The energy of the unit mass is defined as: $\varepsilon = \varepsilon_0(\rho) + \frac{3}{2} \Re T + \frac{\sigma T^4}{\rho}$, where $\Re$ - gas constant, σ - constant radiation density, and $\varepsilon_0(\rho) = \int\limits_0^\rho \frac{P_0(\tilde{\rho})}{\tilde{\rho}^2} \mathrm{d}\tilde{\rho}$.

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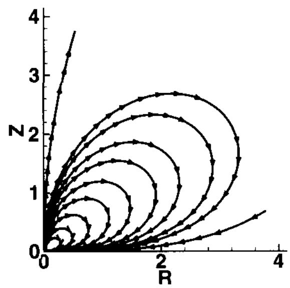

Fig. 1. Initial poloidal magnetic field.

The neutrino losses from Urca processes are defined by relation [7]:

$$f(\rho,T) = \frac{1.3\cdot 10^9 æ(\overline{T})\overline{T}^6}{1+(7.1\cdot 10^{-5}\rho\overline{T})^{\frac{2}{5}}} \quad \mathrm{erg}\cdot \mathrm{g}^{-1}\cdot \mathrm{c}^{-1}, \tag{2}$$

$$æ(\mathrm{T}) = \begin{cases} 1, & \overline{T}<7, \\ 664.31+51.024(\overline{T}-20), & 7\le\overline{T}\le 20, \\ 664.31, \overline{T}>20, \overline{T}=T\cdot 10^{-9}. \end{cases} \tag{3}$$

Neutrino losses from pair annihilation, photo-production and plasma were also taken into account. These type of the neutrino losses have been approximated by the interpolation formulae from [9]: $Q_{tot} = Q_{pair}+Q_{photo}+Q_{plasm}$ These three terms can be written in the following general form:

$$Q_d = K(\rho,\alpha)e^{-c\xi}\frac{a_0+a_1\xi+a_2\xi^2}{\xi^3+b_1\alpha+b_2\alpha^2+b_3\alpha^3}. \tag{4}$$

For $d=pair$, $K(\rho,\alpha)=g(\alpha)e^{-2\alpha}$, $g(\alpha)=1-\frac{13.04}{\alpha^2}+\frac{133.5}{\alpha^4}+\frac{1534}{\alpha^6}+\frac{918.6}{\alpha^8}$; For $d=photo$, $K(\rho,\alpha)=(\rho/\mu_Z)\alpha^{-5}$; For $d=plasm$, $K(\rho,\alpha)=(\rho/\mu_Z)^3$; $\xi=\left(\frac{\rho/\mu_Z}{10^9}\right)^{1/3}\alpha$. Here $\mu_Z=2$ is number of nucleons per electron. Coefficients c, a_i, b_i for different d are given in [9].

The general formula for neutrino losses in non-transparent star has been written in the following form: $F(\rho,T)=(f(\rho,T)+Q_{tot})e^{-\frac{\tau_\nu}{10}}$. The multiplier $e^{-\frac{\tau_\nu}{10}}$, where $\tau_\nu = S_\nu n l_\nu$ restricts neutrino flux for non zero depth to neutrino interaction with matter τ_ν. The cross-section for this interaction S_ν was represented in the form $S_\nu = \frac{10^{-44}T^2}{(0.5965\cdot 10^{10})^2}$, the nucleons concentration is: $n=\frac{\rho}{m_p}$, $m_p = 1.67\cdot 10^{-24}$g. The characteristic length scale l_ν which defines the depth for the neutrino absorption, was taken to be equal to the characteristic length of the density variation, as $l_\nu = \frac{\rho}{|\nabla\rho|} = \frac{\rho}{((\partial\rho/\partial r)^2+(\partial\rho/\partial z)^2)^{1/2}}$. This value monotonically decreases when moving to the outward boundary, from a maximum in the center. It approximately determines to the depth of the neutrino absorbing matter. The multiplier 1/10 was applied because in the degenerate matter of the hot neutron star only part of the nucleons

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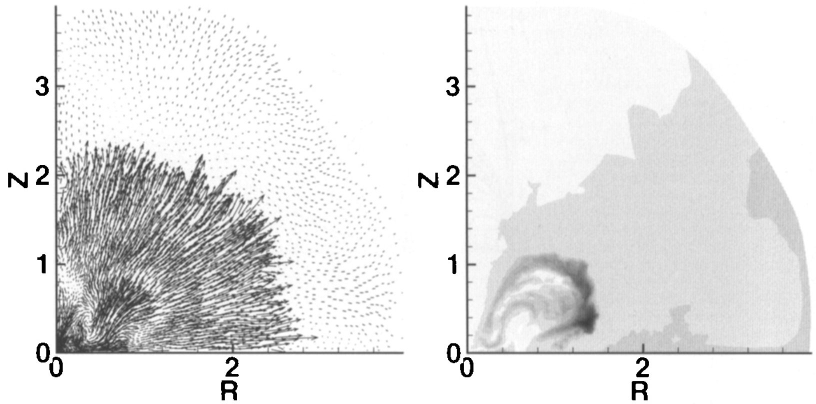

Fig. 2. Velocity field (left plot) and specific angular momentum $v_\varphi r$ (right plot) at $t = 0.191$s after turning on the magnetic field. The darker parts at the right plot correspond to the larger angular momentum.

with the energy near Fermi energy (it was taken $\approx 1/10$) takes part in the neutrino interaction processes.

3 Results

For the numerical simulations we have used implicit Lagrangian difference scheme on triangular grid with grid reconstruction. For the description of the applied numerical method see, for example, [3] and references therein. The number of knots of the triangular grid was about 5000.

As a first stage of the MRS mechanism we have calculated a collapse of rotating star, leading to differentially rotating configuration. After the collapse the star (core of evolved massive star) consists of an almost rigidly rotating neutron star with radius $\sim$ 10 km which rotates with the period $\sim$ 0.001 sec, and large, differentially rotating envelope.

After formation of the differentially rotating configuration the initial poloidal magnetic field was switched on (Fig. 1).

The energy of the initial magnetic field was $E_{mag0} = 10^{-6} E_{grav}$. Where E_{mag0} - is the energy of the initial magnetic field, E_{grav} - is the gravitational energy of the collapsed star.

Due to the differential rotation the toroidal component of the magnetic field is increasing with time. The magnetic pressure grows and produces a compression MHD wave, which moves through the envelope with steeply decreasing density. Soon after appearing this wave transforms into the MHD shock, which throws away part of the matter of the envelope. The MHD shock front is clearly seen at the velocity field plot (Fig. 2 - left plot). The magnetic

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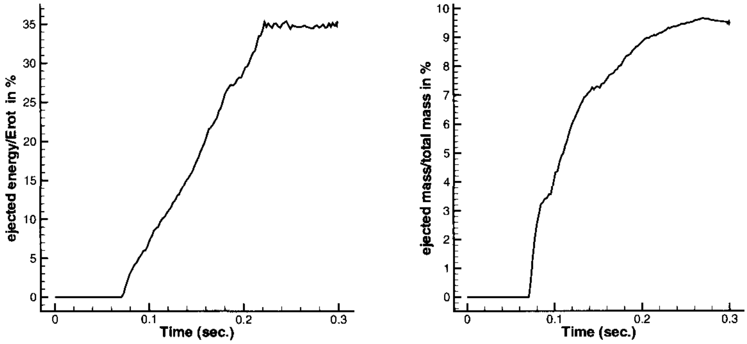

Fig. 3. Time evolution of the (ejected energy)/(rotational energy) in percent (left plot) and (ejected mass)/(total mass) in percent (right plot).

field transmits angular momentum of the neutron star outwards (Fig. 2 - right plot).

Results of our simulations show that the energy of the supernova explosion is about 1.12×10^{51} erg (35% of the rotational energy of the star). The explosion ejects about 0.11 $M_{\odot}$ ($\sim$ 9.7% of the mass of the star). At the Fig. 3 the time evolution of the ejected mass and ejected energy are presented.

Detailed description of the results of the simulations of the MRS will be published elsewhere.

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