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Magnetorotational supernovae and jet formation

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Abstract. A magnetorotational mechanism of explosion is at work in core-collapse supernova. The main energy source is the rotational energy of the new born neutron star, and the magnetic field induces the transformation of this energy into the energy of the expanding shock wave. The amount of energy released by this mechanism is enough to explain the observations. The development of the magnetorotational differential instability is studied. A jet is formed at a dipole-like magnetic field configuration.

1. Introduction

Core-collapse SNe explode at the end of evolution of massive stars, with initial mass larger than $\sim 12M_{\odot}$. During the core collapse and formation of a neutron star, gravitational energy release $\sim 6 \cdot 10^{53}$ erg, is carried away by neutrinos. The first mechanism (Colgate and White 1966) of the explosion in a core-collapse (CC) SN was based on heating the infalling outer layers by a huge energy flux carried by neutrinos. More accurate calculations revealed that the energy of such explosion is not enough for the explanation of observations, and results of modified neutrino models are still not definite, see e.g. Bisnovatyi-Kogan (2011). Neutrino convection (Epstein, 1979) carries out the inner hot layers, leading to radiation of a more energetic neutrino flux which heats stronger the outer layers, leading to formation of a stronger shock. 2-D calculations do not give a definite answer about the efficiency of neutrino convection, 3-D models give even less powerful explosions. Convective eddies of a larger size are more efficient in heating the envelope by neutrino flux, bringing matter from deeper hotter layers. In 2-dimensional systems the convective energy goes to larger scale eddies, while in a realistic 3-D case the energy goes to smaller eddies. The decrease of the size of convective eddies in realistic 3-D problems makes 3-D models less effective. The magnetorotational mechanism (Bisnovatyi-Kogan, 1970) investigated by many groups shows its efficiency in explanation of CCSN explosions.

2. Magnetorotational mechanism of explosion

In magnetorotational explosion (MRE) the transformation of the rotational energy of the neutron star into explosion energy takes place by means of the mag-

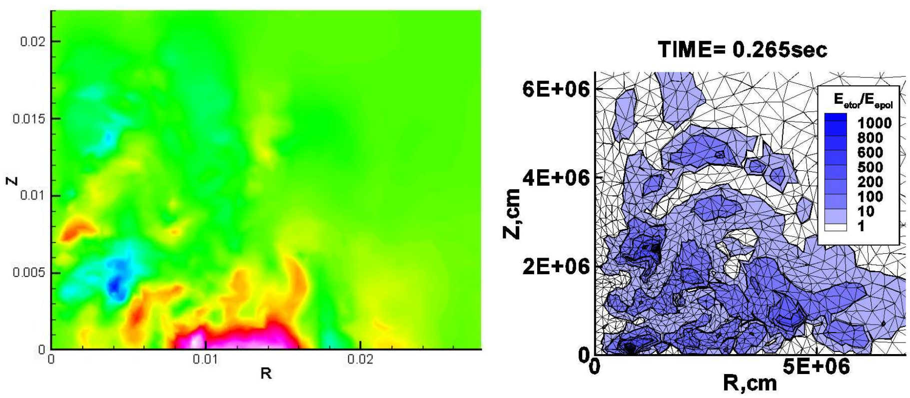

Figure 1. Toroidal magnetic field distribution at its maximal energy for the quadrupole field (left). The ratio of the toroidal to the poloidal magnetic energy, $E_{\rm tor}/E_{\rm pol}$ at $t = 265$ ms for the case $H_0 = 10^9$ Gs, $E_{\rm rot,0}/E_{\rm grav,0} = 1\%$ (right). Reproduced from Bisnovatyi-Kogan et al. (2015).

netic field. In differentially rotating magnetized new born neutron stars the radial component of the magnetic field is twisted, and magnetic pressure becomes very high, producing MHD shock by which the rotational energy is transformed to the explosion energy. Calculations of MRE have been done by Bisnovatyi-Kogan et al. (1976), using one-dimensional MHD equations, for the case of cylindrical symmetry. The calculations show that the outer part of the envelope expands with large velocity, carrying out a considerable part of rotational energy and rotational momentum. MRE has an efficiency about 10% of the rotational energy, the ejected mass is ≈ 0.1 of the star mass, and the explosion energy $\approx 10^{51}$ erg. Ejected mass and explosion energy depend weekly on the initial parameter $\alpha = E_{\rm mag}/E_{\rm grav}$. Explosion time is $t_{\rm expl} \sim \frac{1}{\sqrt{\alpha}}$. Small α values are difficult for calculations with explicit numerical schemes because of the Courant restriction on the time step, The system of equations is "hard", where α determines the "hardness".

3. 2-D calculations

The numerical method used in the simulations is based on the implicit operator-difference, completely conservative scheme on a Lagrangian triangular grid of variable structure, with grid reconstruction. The implicitness of the applied numerical scheme allows for large time-steps (see Ardelyan and Chernigovskii 1984, Ardelyan et al. 1996). The scheme is fully conservative, which includes conservation of mass, momentum and total energy, and correct transitions between different types of energies. MHD equations with self-gravitation, and infinite conductivity have been solved. The problem has an axial symmetry ($\frac{\partial}{\partial \phi} = 0$), and the symmetry with respect to the equatorial plane ($z = 0$). An initial toroidal current J_ϕ was taken at the initial moment producing $H_r,\ H_z$. The initial magnetic field of dipole-like symmetry is obtained at opposite directions of the current in both hemispheres. Neutrino cooling was calculated using a variant of a flux-limited method (Ardelyan et al., 2005).

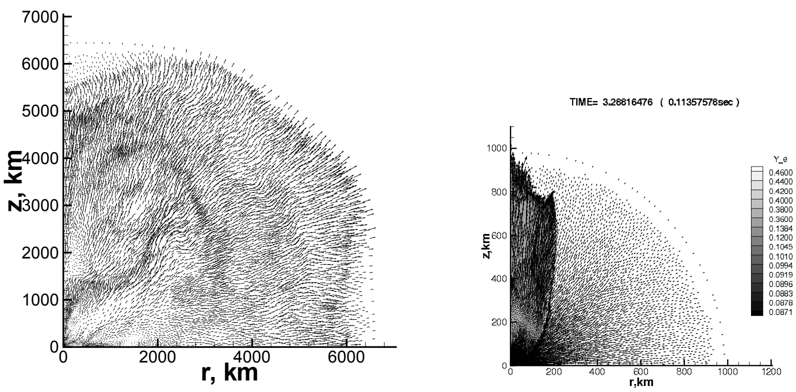

Figure 2. The velocity field (outflow) for the time moment, $t = 0.25\,s$, from Moiseenko et al. (2006, left). Jet formed for the initial uniform field with $H_{0z} = 10^9$ Gs, $E_{\mathrm{rot},0}/E_{\mathrm{grav},0} = 0.8\%$. The hatched zone corresponds to the outflowing jet, ejected from deep layers of the star with high neutronization, low $Y_e = n_e/n_b$, where n_e is the electron concentration, n_b is a total baryon concentration (free and in nuclei, right) . Left panel reproduced from Bisnovatyi-Kogan et al. (2015).

Magnetic field is amplified due to twisting by the differential rotation, and subsequent development of the magnetorotational instability. The field distribution for initial quadrupole-like magnetic field with $\alpha = 10^{-6}$, at the moment of the maximal energy of the toroidal magnetic field is represented in Fig.1. A maximal value of $B_\phi = 2.5 \cdot 10^{16}$ Gs was obtained. The magnetic field at the surface of the neutron star after the explosion is $B = 4 \cdot 10^{12}$ Gs. The larger part of the gravitational energy, released during the collapse, is carried away by neutrinos. The total energy ejected in the kinetic form is $\sim 0.6 \cdot 10^{51}$ erg, and the total ejected mass is equal to $\sim 0.14 M_\odot$. The simulations were done for the initial poloidal magnetic field of quadrupole (Ardelyan et al. 2005) and of dipole (Moiseenko et al. 2006) symmetry types. The initial ratios between the rotational and gravitational, and also between the internal and gravitational energies of the star had been chosen as: $\frac{E_{\mathrm{rot}}}{E_{\mathrm{grav}}} = 0.0057$, $\frac{E_{\mathrm{int}}}{E_{\mathrm{grav}}} = 0.727$. The ratio between the initial magnetic and gravitational energies was chosen as 10^{-6}. The initial poloidal magnetic field in the center was $\sim 3.2 \times 10^{13}$ Gs. The magnetic field works as a piston for the originated MHD shock. The simulation of the MR supernova explosion for various initial core masses and rotational energies was done by Bisnovatyi-Kogan et al. (2008). The explosive energy increases with the mass of the core, and the initial rotational energy. The energy released in MRE, $(0.5 - 2.6) \times 10^{51}$ erg, is sufficient to explain Types II and Ib supernovae with collapsing cores. Note that magnetorotational explosion (MRE) is supported mainly by the magnetic pressure, which is hardly connected with the scale of eddies, so we may expect the same efficiencies of MRE in 2 and 3-D numerical models.

4. Magnetorotational differential instability

Magnetorotational differential instability (MRDI) leads to exponential growth of magnetic fields. Different types of MRI have been studied by Velikhov (1959) and Spruit (2002). In our calculations MRDI starts to develop when the ratio of the toroidal to poloidal magnetic energies becomes large, what corresponds to the instability studied by Tayler (1973). In 1-D calculations MRDI is absent because of a restricted degree of freedom, and time of MRE increases with α as $t_{\rm expl} \sim \frac{1}{\sqrt{\alpha}}$, $\alpha = \frac{E_{\rm mag,0}}{E_{\rm grav,0}}$. Due to development of MRDI the time of MRE depends on α much weaker. The MRE happens when the magnetic energy becomes comparable to the internal energy, at least in some parts of the star. MRDI leads to exponential growth of the magnetic energy. The total time of MRE in 2-D grows **logarithmically** with decreasing of α, $t_{\rm expl} \sim -\log \alpha$ in 2-D calculations (Ardelyan et al. 2005, Moiseenko et al. 2006), giving the following explosion times $t_{\rm expl}$ (in arbitrary units): $\alpha = 0.01,\ t_{\rm expl} = 10, \quad \alpha = 10^{-12},\ t_{\rm expl} = 10^6$ in 1-D, and $\alpha = 10^{-6},\ t_{\rm expl} \sim 6, \quad \alpha = 10^{-12},\ t_{\rm expl} \sim 12$ in 2-D.

5. Jet formation in MRE

Jet formation in MRE happens at the initial magnetic field of a dipole-like structure, when the ejected mass is collimated along the rotational axis (Moiseenko et al. 2006), see Fig. 2. Simulations of the MR supernova have been made with the equation of state suggested by Shen et al. (1998). A comparison of our results for the initially uniform magnetic field, with the results of Takiwaki et al. (2004) and Takiwaki et al. (2009), for the same initial and boundary conditions, shows good agreement for a strong initial field ($H_0 = 10^{12}$ Gs), while for a weaker field ($H_0 = 10^9$ Gs) we get a mildly collimated jet-like explosion. MRDI is developed in the case of a weaker initial magnetic field, and it is not present in the calculations with stronger field, see Figs. 3,4. In Fig. 2 the ratio of the toroidal magnetic energy to the poloidal one ($E_{\rm tor}/E_{\rm pol}$) is represented for the case $H_0 = 10^9$ Gs, and $E_{\rm rot,0}/E_{\rm grav,0} = 1\%$. The toroidal magnetic energy dominates over the poloidal one in the significant part of the region. The MDRI is well-resolved on our triangular grid. At $H_0 = 10^9$ Gs the rotational energy has two maxima. The first contraction is accompanied by the strong growth of the rotational energy and coincides with the first maximum of the density. Development of the magnetorotational instability leads to a rapid growth of the magnetic field, and a large angular momentum flux from the core. It stops the expansion, and leads to the second contraction phase which is not transformed into expansion, because of the rapid decrease of angular momentum in the core.

6. Asymmetry of the explosion

The symmetry with respect to the equatorial plane. can be violated due to the MRI, the simultaneous presence of the initial dipole and quadrupole -like magnetic fields (Wang et al. 1992), and the initial poloidal and toroidal magnetic fields of opposite symmetries (Bisnovatyi-Kogan and Moiseenko 1992). When rotational and magnetic axes do not coincide the whole picture of the explosion

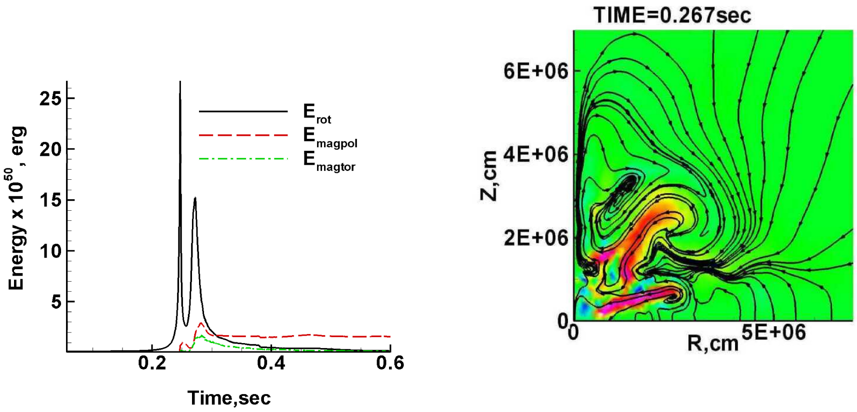

Figure 3. Time evolution of rotational $E_{\rm rot}$ (solid line), magnetic poloidal $E_{\rm mag,pol}$ (dashed line) and magnetic toroidal $E_{\rm mag,tor}$ (dash-dotted line) energies for $H_0 = 10^9$ Gs, $E_{\rm rot,0}/E_{\rm grav,0} = 1\%$ (left). Developed MDRI at $t = 267$ms for the same parameters: contour plot - the toroidal magnetic field, arrow lines - poloidal magnetic field (right). Reproduced from Bisnovatyi-Kogan et al. (2015).

process is three dimensional, but the magnetic field twisting happens around the rotational axis (Mukami et al. 2008). We may expect the kick velocity of the neutron star to be strongly correlated with its spin direction. During the phase of MRE explosion the regular component of magnetic field may exceed temporally 10^{16} Gs (Ardelyan et al. 2005, Moiseenko et al. 2006), when the neutrino cross-section depends on the magnetic field strength, and due to strong anisotropy of the neutrino flux. The kick velocity in this case may reach several thousands km/s (Bisnovatyi-Kogan 1993), as in most rapidly moving radio pulsars (Vlemmings et al. 2005). Analysis of observations of pulsars shows that rotation and velocity vectors of pulsars are aligned, as is predicted by the MR supernova mechanism. This alignment was found by Smirnova et al (1996), and was confirmed by Johnson et al.(2005), Johnson et al.(2007), and Noutsos et al. (2012).

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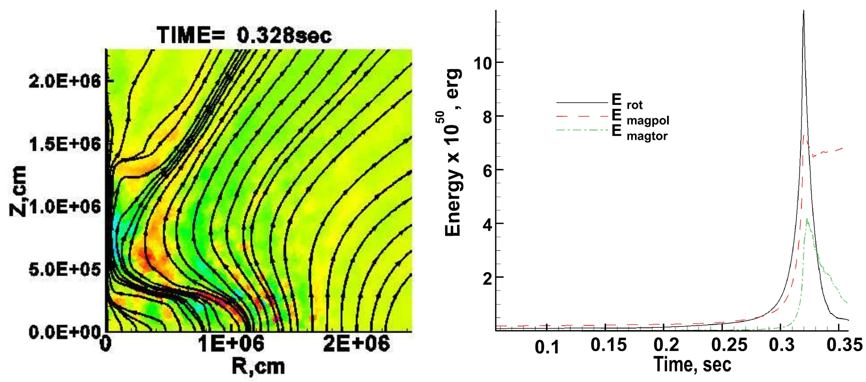

Figure 4. Absence of MDRI for the case $H_0 = 10^{12}$ G, $E_{rot0}/E_{grav0} =$ 1%. Notations are as in Fig.3. Reproduced from Bisnovatyi-Kogan et al. (2015).

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