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Magnetorotational Supernovae - The Supernova Mechanism That Works

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Abstract. Our 2D simulations of the magnetorotational mechanism (MRM) of the explosions of the core collapse supernovae show that MRM produces enough energy for the explanation of such supernova ($0.5-0.6\times10^{51}$ erg). The amplification of the magnetic field due to the differential rotation leads to formation of the MHD shock. The "shape" of the supernova explosion depends qualitatively on the symmetry type of the initial magnetic field. The magnetorotational instability (MRI) was found in the simulations which significantly reduces the evolution time of the magnetic field amplification. The MRM can produce one sided jets and kicks. For the simulations we have used a specially developed numerical method based on the completely conservative implicit Lagrangian numerical scheme on the triangular Lagrangian grid of a variable structure.

Key words. MHD-supernovae: general

1. Introduction

The reliable theoretical explanation of the core collapse supernova explosion is still one of the most complicated and interesting problems of modern astrophysics. The prompt explosion due to the bounce shock and neutrino driven mechanisms do not produce the supernova explosion with a sufficient level of confidence.

The rotation and magnetic fields are important ingredients of many core collapse supernovae. Bisnovatyi-Kogan (1970) suggested to take into account these factors for explanation the core collapse supernova event. The idea of the MRM is the transformation of the rotational energy of the new born neutron star into the explosion energy by means of the magnetic field. The core collapse is nonuniform and the collapsed core rotates differentially. This differential rotation of the core generates a toroidal component of the magnetic field (if it did not exist earlier). The toroidal field is amplified with the time. In another words the magnetic pressure near the boundary of the forming proto neutron star ($\sim 10-20$km from the center) grows and produces a compression MHD wave. This wave moves through the envelope of the star along a steeply decreasing density profile and quickly transforms into the fast MHD shock which produces the supernova explosion.

We solve numerically a set of the ideal MHD equations with the infinite conductivity and self-gravitation. We use a realistic equation

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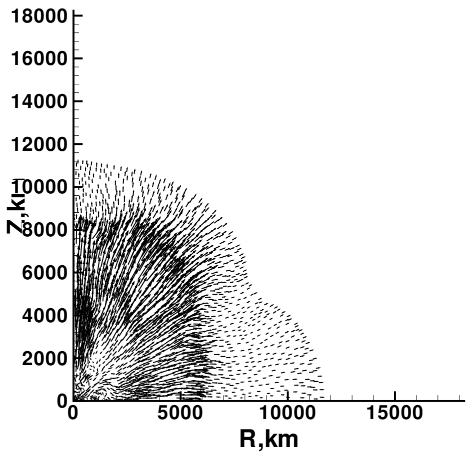

Fig. 1. The velocity field for the magnetorotational supernova with the initial *dipole* like magnetic field at $t = 1.06$s after beginning of the evolution of the toroidal magnetic field.

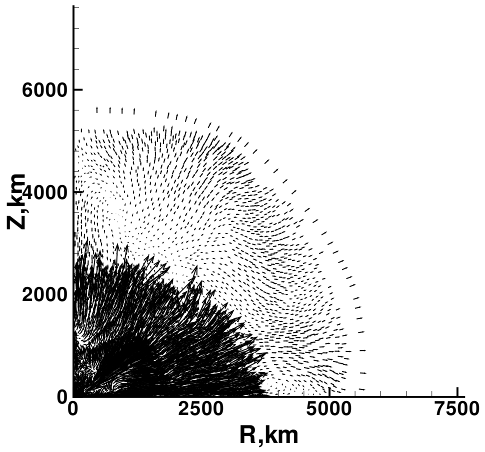

Fig. 2. The velocity field for the magnetorotational supernova with the initial *quadrupole* like magnetic field at $t = 0.2$s after beginning of the evolution of the toroidal magnetic field.

of state, and take into account neutrino losses. The details of the equation of state and formulae for the neutrino losses are described in detail by Ardeljan et al. (2004) and Ardeljan et al. (2005).

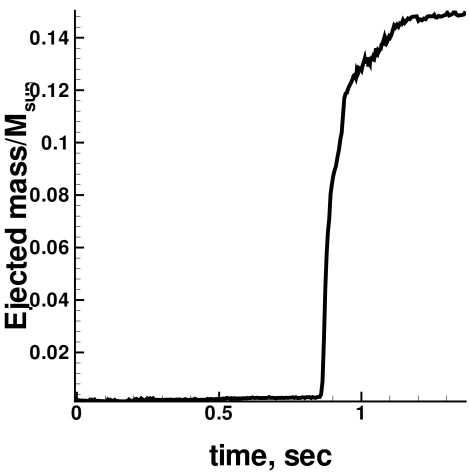

Fig. 3. Time evolution of the ejected mass for the initial dipole-like magnetic field.

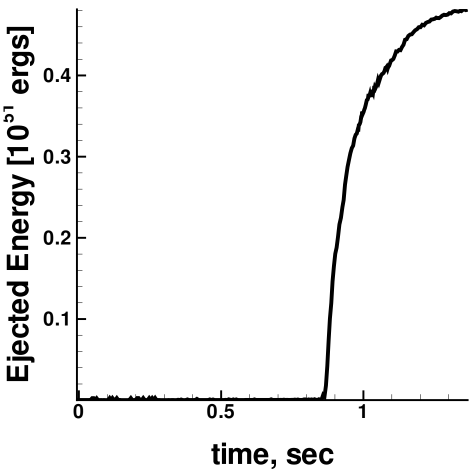

Fig. 4. Time evolution of the ejected energy for the initial dipole-like magnetic field.

For the simulations we use an implicit completely conservative Lagrangian numerical scheme on the triangular Lagrangian grid of a variable structure (see Ardeljan et al. (2005) and references therein).

Our simulations show that MRM leads to the supernova explosion, the ejected energy (explosion energy) is about $0.5 - 0.6 \times 10^{51}$erg what is enough for the explanation of the

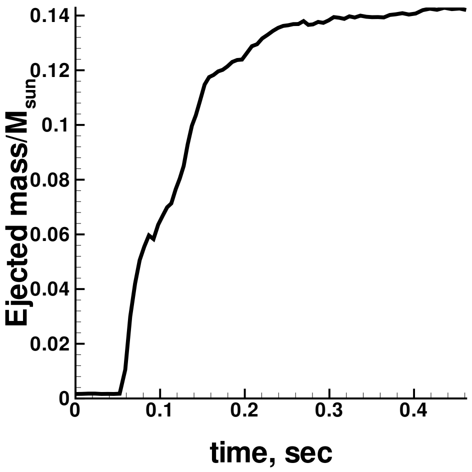

Fig. 5. Time evolution of the ejected mass for the initial quadrupole-like magnetic field.

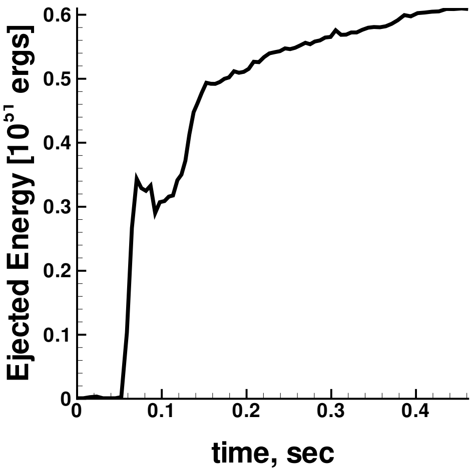

Fig. 6. Time evolution of the ejected energy for the initial quadrupole-like magnetic field.

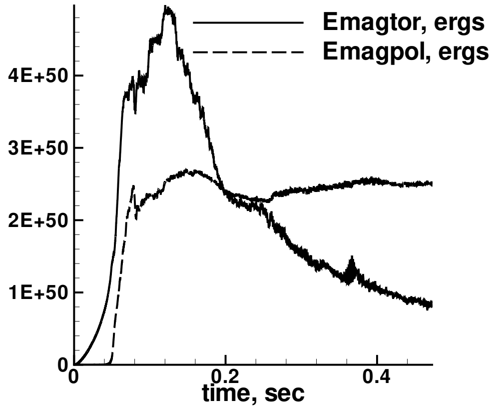

Fig. 7. Time evolution of the toroidal and poloidal parts of the magnetic energy during the magnetorotational explosion for the initial quadrupole-like magnetic field.

core collapse supernova. It was found that the 'shape' of the supernova explosion caused by MRM qualitatively depends on the configuration (symmetry type) of the initial magnetic field. The dipole-like initial poloidal magnetic field leads to the formation of a mildly collimated proto-jet while the quadrupole-like initial poloidal field results in the supernova explosion which develops mainly near equatorial plane.

The MRI was found in our simulations. The appearance of MRI leads to the exponential growth of both toroidal and poloidal components of the magnetic field shortening significantly the supernova explosion time.

2. Magnetorotational supernovae

To simulate MRM we first have calculated in Ardeljan et al. (2004) the core collapse without magnetic field . After the collapse we have obtained a differentially rotating configuration which consists of the proto neutron star with radius $\approx 10 \div 15$km and expanded shell. The collapse and the appeared bounce shock do not produce the supernova explosion. After reaching a stationary differentially rotating configuration the initial poloidal magnetic field was "turned on". At the moment of "turning on" of the poloidal magnetic field we have started counting the time anew. For the simulations we used two different types of the initial magnetic field, namely dipole-like and quadrupole-like fields. The main parameter which defines the characteristic time of the magnetorotational

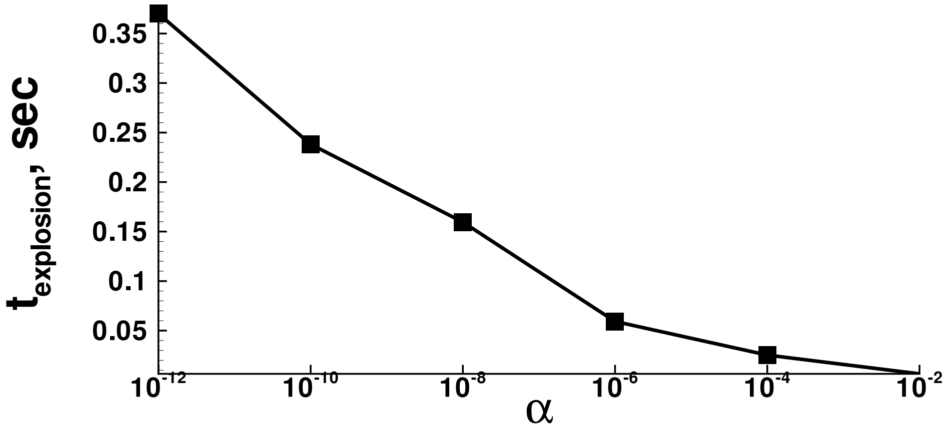

Fig. 8. Dependence of the explosion time from α.

explosion is a ratio between the initial magnetic (E_{mag}) and the initial gravitational energies $\alpha = E_{mag}/E_{grav}$. The results of the simulations described here, correspond to $\alpha = 10^{-6}$.

2.1. Magnetorotational supernova with the dipole-like initial magnetic field

The dipole-like initial magnetic field leads to the formation of the explosion in the form of mildly collimated proto-jets which are developing along the rotational axis. The velocity field of the supernova explosion with such initial field is represented in Fig.1

Magnetorotational supernova explosion with the initial dipole-like magnetic field gives the ejected energy about 0.5×10^{51}erg, and the ejected mass about $0.14 M_{\odot}$. The time evolution of the ejected mass and energy due to magnetorotational explosion with initial dipole-like magnetic field are represented in Figs.3,4.

The ejection of the mass and energy starts at ≈ 0.86s after the beginning of the evolution of the toroidal magnetic field. The details of the magnetorotational explosion with the initial dipole-like magnetic field will be published elsewhere.

2.2. Magnetorotational supernova with quadrupole-like initial magnetic field

The magnetorotational explosion with the quadrupole-like initial magnetic field develops mainly near the equatorial plane (Fig. 2) and its time evolution is a little bit shorter than for the dipole-like initial magnetic field. The time evolution of the ejected mass and energy for this case are given in Figs.5,6 from Ardeljan et al. (2005).

In the case of the initial quadrupole-like magnetic field the amount of the ejected mass is approximately the same as for the quadrupole-like field $\sim 0.14 M_{\odot}$. The amount of the ejected energy is $\sim 0.6 \times 10^{51}$erg.

The ejection of the mass and energy for the quadrupole-like initial magnetic field starts much earlier (at $\approx t = 0.045$s) than in the case of the dipole.

3. The magnetorotational instability in magnetorotational supernova

In 1D simulations of MRM (Ardelyan et al. (1979)) it was shown that evolution time of the magnetorotational explosion depends on α as $t_{exploison} \sim \frac{1}{\sqrt{\alpha}}$. We have done simulations of MRM for a wide range of the initial values of the magnetic energy ($\alpha = 10^{-2} \div 10^{-12}$). The amounts of the ejected energy and the mass are approximately the same for all variants. It was found in 2D simulations that at the initial stage the toroidal magnetic field grows linearly (the energy of the toroidal magnetic field grows as quadratic function). At the developed stage both components of the magnetic field begin to grow exponentially due to development of the MRI (Fig.7). In the paper of Ardeljan et al. (2005) we have considered a toy model which shows the development MRI in 2D case when there is no direct influence of the toroidal field on to the poloidal field, and therefore there is no dynamo action. The dependence of the explosion time on the parameter α is given in Fig.8. For $\alpha \geq 10^{-5}$ the dependence $t_{exploison} \sim \frac{1}{\sqrt{\alpha}}$ holds approximately, while for the smaller (and more realistic) values of α the dependence of $t_{exploison}$ on α changes and has the following form $t_{explosion} \sim -\frac{1}{lg(\alpha)}$.

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