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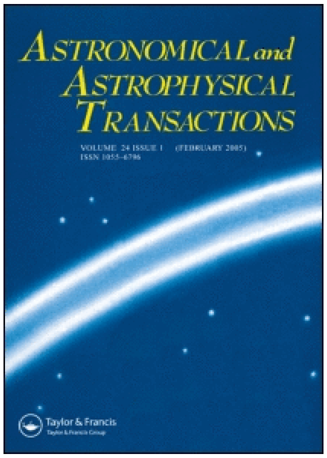

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# Core-collapse supernovae: magnetorotational mechanism

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The results of two-dimensional numerical simulations of the magnetorotational (MR) supernova mechanism are presented. The shape of the explosion qualitatively depends on the symmetry type of the initial magnetic field. For the initial quadrupole-type magnetic field, the MR supernova explosion develops mainly near the equatorial plane while, for the initial dipole magnetic field, the MR supernova explosion has the shape of a mildly collimated proto-jet. The ejected energy in the MR supernova explosion in our simulations was about (0.5–0.6) × $10^{51}$ erg. MR instability was found during simulations of the MR supernova explosion and leads to the exponential growth of both the toroidal and the poloidal magnetic fields.

*Keywords*: Supernova; Collapse; Neutron stars; Magnetic fields; Hydrodynamic simulations

## 1. Introduction

The problem of the explanation of the core-collapse supernova (SN) event is one of the interesting and long-standing problems in astrophysics. Mechanisms based on the bounce shock energy or neutrino interaction with the matter of a presupernova star do not lead to the SN explosion.

The magnetorotational (MR) mechanism for the core-collapse SN explosion was suggested by Bisnovatyi-Kogan [1] in 1970. The main idea of the MR mechanism is to transform part of the rotational energy of presupernova into the radial kinetic energy (explosion energy). Because the collapse is not uniform, the iron core rotates differentially. Differential rotation leads to the appearance and amplification of the toroidal component of the magnetic field. The increase of the magnetic field means amplification of the magnetic pressure with time. A compression wave appears near the region of the extremum of the magnetic field. This compression wave moves outwards along a steeply decreasing density profile. In a short time it transforms to a fast magnetohydrodynamic shock wave. When the shock reaches the surface of the presupernova, it ejects some of the matter and energy of the presupernova star. This ejection can be interpreted as an explosion of the core-collapse SN star. The first one-dimensional (1D) simulations of an MR SN explosion were presented in [2] (see also [3]).

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Our results of simulations of the MR SN explosion mechanism show that this mechanism produces an explosion of energy (0.5–0.6) $\times 10^{51}$ erg. These values of SN explosion energy correspond to estimations made from core-collapse SN observations.

It was found that the shape of the MR SN explosion qualitatively depends on the configuration (symmetry type) of the magnetic field. The initial field, which has a quadrupole-type symmetry, leads to the MR explosion that develops predominantly near the equatorial plane, while the initial dipole-type field causes an SN explosion in the form of a mildly collimated jet that develops along the axis of rotation.

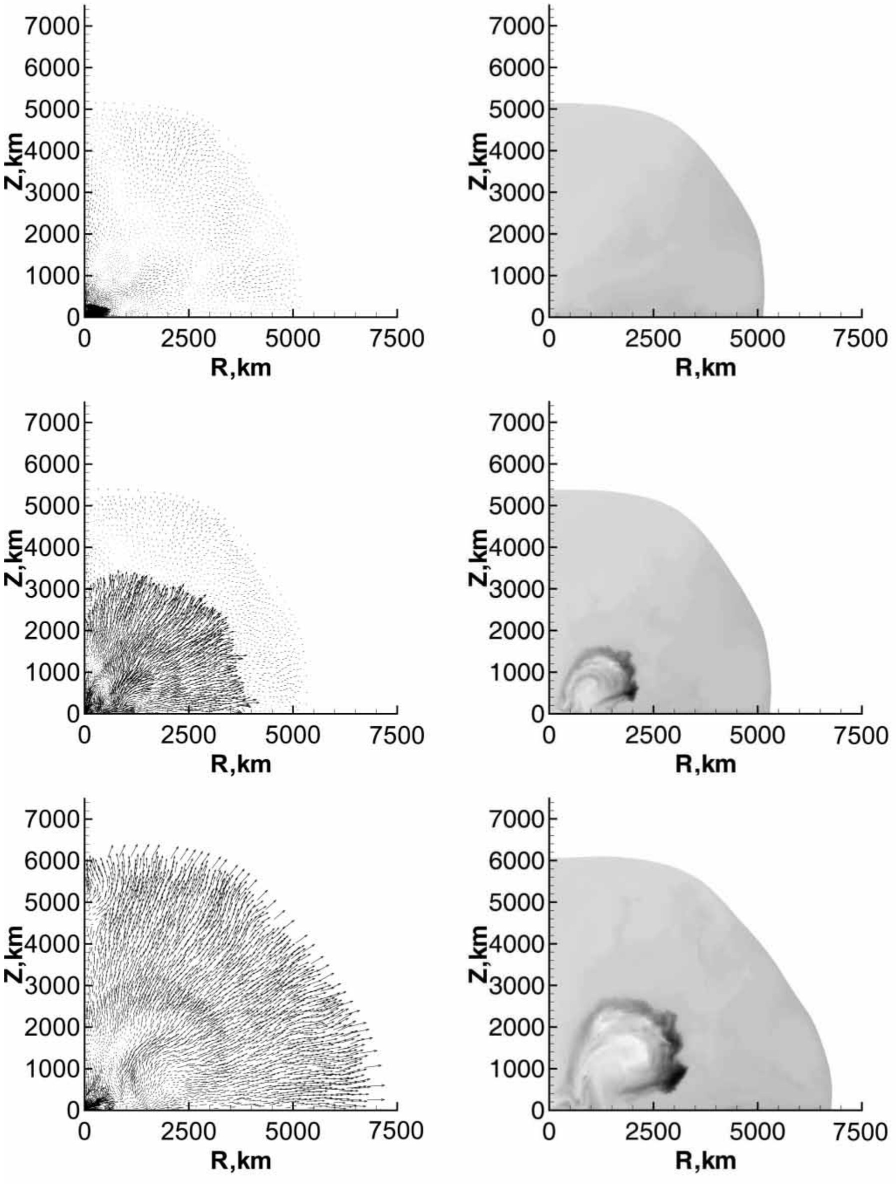

Figure 1. (a) Time evolution of the velocity field and (b) time evolution of the specific angular momentum $v_\varphi r$ for the time moments $t = 0.07$, 0.20 and 0.30 s for the initial *quadrupole*-like magnetic field.

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Magnetorotational instability (MRI) was revealed in two-dimensional (2D) simulations of the MR SN mechanism and leads to the exponential growth of both the poloidal and the toroidal components of the magnetic field, significantly reducing the time of the MR SN explosion in comparison with 1D simulations [2].

For the 2D magnetohydrodynamic simulations we used a specially developed numerical code based on the implicit, completely conservative Lagrangian scheme on a triangular grid of variable structure (see [4] and references therein).

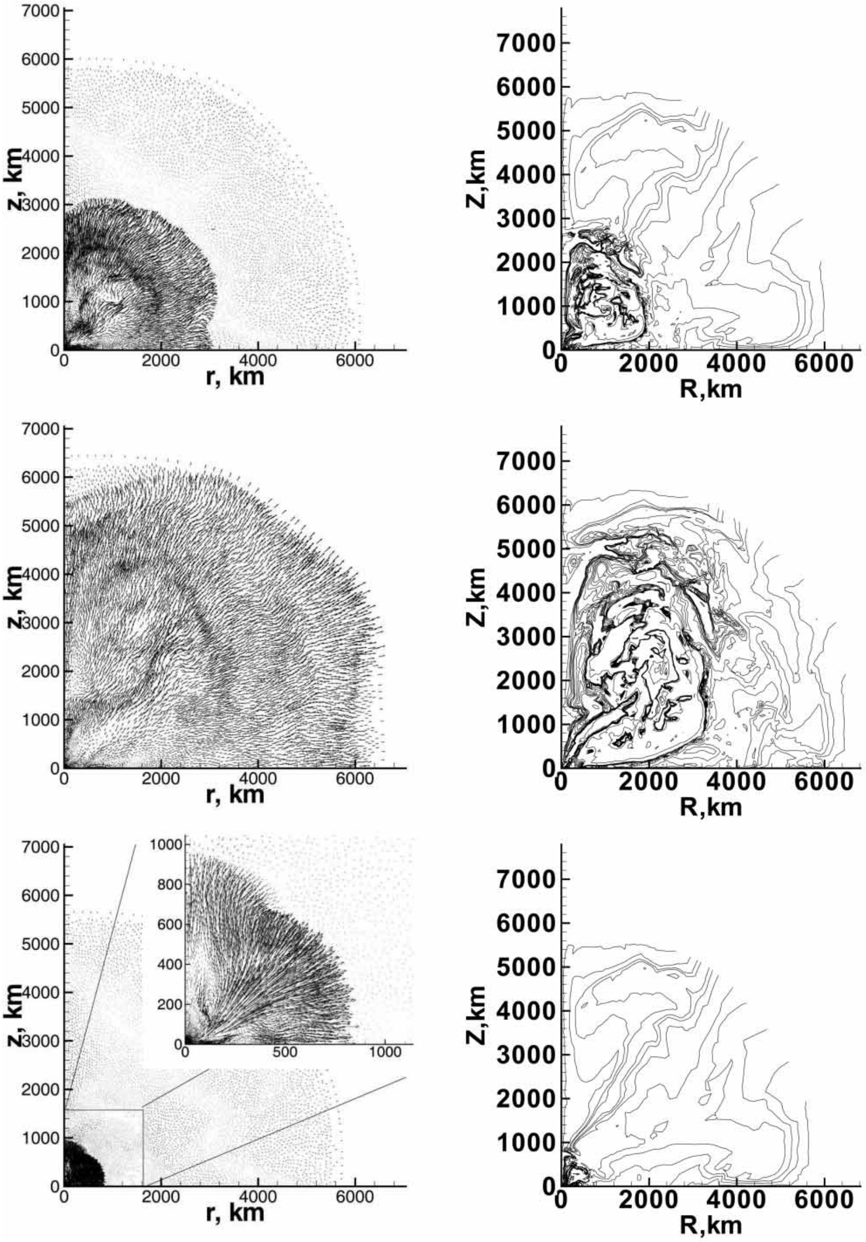

Figure 2. (a) Time evolution of the velocity field and (b) time evolution of the specific angular momentum $v_\varphi r$ for the time moments $t = 0.075$, 0.1 and 0.25 s for the initial *dipole*-like magnetic field.

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## 2. Magnetorotational supernova explosion

An MR explosion with an initial quadrupole-like magnetic field has been described in detail in [5]. After the core collapse the presupernova rotates differentially. The toroidal component of the magnetic field appears and grows linearly with time at the initial stage of the MR explosion. When the toroidal magnetic field reaches a certain value, its linear growth changes to the exponential growth of the toroidal and poloidal components because of the development of the MRI. A toy model for the qualitative explanation of the MRI in an MR SN was suggested in [5]. An MR SN explosion with an initial quadrupole-like magnetic field results in an explosion which develops mainly near the equatorial plane. In figure 1(a) the time evolution of the velocity field and in figure 1(b) the time evolution of the specific angular momentum are shown for the initial quadrupole-like field. At the end of our simulations we have found that the MR SN with an initial quadrupole-like magnetic field produces an explosion energy of about $0.6 \times 10^{51}$ erg and ejects about $0.14 M_{\odot}$ of mass.

Simulations of the MR SN with an initial magnetic field of dipole-like symmetry leads to a qualitatively different result in the shape of explosion [6]. In this case the MR explosion develops mainly along the axis of rotation and forms a mildly collimated proto-jet (figure 2). The amounts of the ejected mass and energy are approximately the same as in quadrupole case, *i.e.* an ejected energy of about $0.5 \times 10^{51}$ erg and an ejected mass of about $0.14 M_{\odot}$. The proto-jet found in our simulations could be collimated when it develops in the extended envelope of the massive star, *i.e.* the progenitor of the core-collapse SN.

The MRI leads to the formation of a chaotic magnetic field structure. In the case of finite conductivity the reconnection of the magnetic field could be important. We have estimated the characteristic time of the reconnection of the magnetic field using the results of our simulations [6]. We found that the characteristic time for the reconnection of the magnetic field for SN parameters used in our simulations is approximately 5 s. The MR SN explosion time in our simulations is about 0.5–1 s, which is significantly less than the characteristic time of the magnetic field reconnection development and does not influence the MR SN significantly.

## 3. Conclusion

The results of 2D simulations of the MR SN explosion mechanism show that it produces an explosion energy which corresponds to the observational values of the explosion energy for core-collapse SNs. The MRI developing in the simulations of the MR SN significantly reduces the explosion time and increases the chaotic magnetic field in the young neutron star [7]. The jet formation may be related to a cosmic gamma-ray burst, connected with an SN.

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