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SUPERNOVA TYPE II: MAGNETOROTATIONAL EXPLOSION

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RESUMEN

Se investiga numéricamente en dos dimensiones el mecanismo magnetorotacional para las explosiones de supernova tipo II. Utilizamos un método implícito lagrangiano que hemos desarrollado en una malla triangular que incorpora la reconstrucción de la malla. Mostramos que la forma de la explosión depende cualitativamente de la configuración inicial del campo magnético poloidal. También hemos hecho simulaciones del problema del colapso de la protoestrella de neutrones. Se demuestra que después del colapso la configuración resultante consta de un núcleo denso que gira rápidamente y es casi rígido, y un envolvente prolato que gira lentamente. La velocidad angular cambia muy rápido en la región de transición entre el núcleo y el envolvente. En tal situación podemos esperar una evolución rápida del componente toroidal del campo magnético debido a la rotación diferencial, que pueda llevar a la explosión.

ABSTRACT

The magnetorotational mechanism for supernova type II explosions is investigated numerically in 2-D. For the simulations we use a specially developed, implicit Lagrangian method on a triangular grid with grid reconstruction. We show that the shape of the explosion qualitatively depends on the initial configuration of the poloidal magnetic field. We also have done simulations of the problem of collapse of the protoneutron star. It was shown that after the collapse the resulting configuration consists of a dense, almost rigid, rapidly rotating core and a prolate, slowly rotating envelope. The angular velocity changes very quickly in the transitional region between the core and the envelope. In such a situation we can expect rapid evolution of the toroidal component of the magnetic field due to differential rotation, which can lead to the explosion.

Key Words: **MAGNETOHYDRODYNAMICS — METHODS: NUMERICAL — STARS: SUPERNOVAE**

1. INTRODUCTION

The problem of supernova type II explosions has not been solved up to now. The different approaches, such as the neutrino convection model, still do not produce an explosion.

It is known that most stars are rotating and are magnetized. The idea of using rotation and magnetic fields to get energy for the supernova explosion was suggested by Bisnovatyi-Kogan (1970). The first 2-D simulations of the collapse of a rotating magnetized star were made by Leblanc & Wilson (1970). After a loss of stability, the rotating, magnetized, presupernova star collapses and forms a differentially rotating configuration. It consists of the dense, almost rigidly rotating core and a light envelope, which rotates much slower than the core. In the transitional region between the core and the envelope the rotation is strongly differential (i.e., angular velocity is rapidly changing with radial coordinate). In such conditions even a weak, initial poloidal magnetic field starts to produce a toroidal component, which grows linearly with time. In the regions of the extrema of the toroidal magnetic energy the magnetic force produced by the toroidal magnetic pressure becomes comparable to the gravitational force and the gradient of the gas pressure.

We briefly describe here the results of our 2-D simulations of the collapse of a rotating, magnetized, protostellar cloud. We show that application of a quadrupole-like initial poloidal magnetic field leads to the ejection of matter mainly near the equatorial plane. The application of the dipole-like magnetic field leads to the formation of the ejection, which develops predominantly along the rotational axis.

We have carried out 2-D simulations of the collapse of the white dwarf and formation of the neutron star with the equation of state of a dense matter, taking into account neutrino losses.

For the simulations we have used a specially developed, implicit, Lagrangian, completely conservative method on a triangular grid with grid reconstruction (see Ardeljan, Bisnovatyi-Kogan, & Moiseenko 2000, and references therein).

2. ROTATING MAGNETIZED CLOUD COLLAPSE

To show the efficiency of the magnetorotational mechanism we have performed 2-D simulations of

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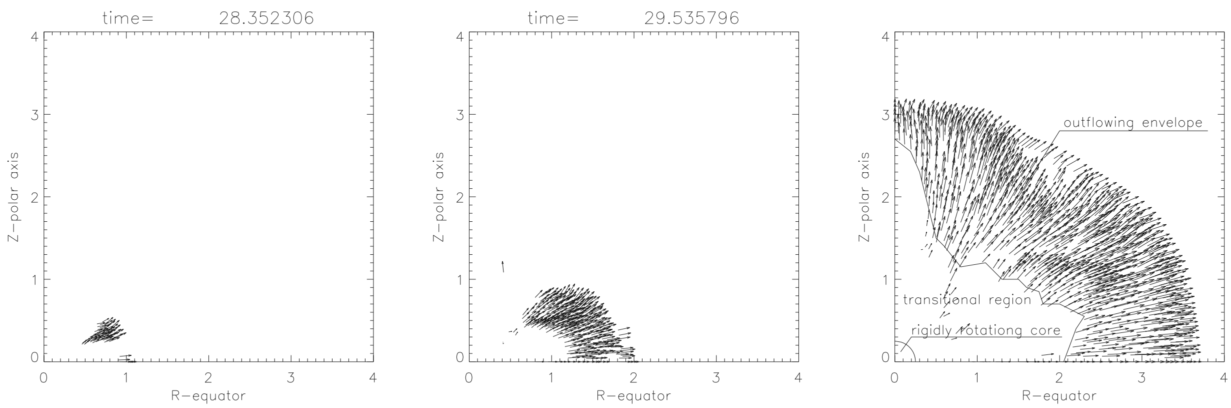

Fig. 1. Time evolution of the velocity field of the ejected part of the envelope during the collapse of a rotating, magnetized cloud.

the problem of the collapse of a rotating, magnetized, protostellar gas cloud. The details of the calculations are presented in Ardeljan et al. (2000).

The time evolution of the velocity field of the ejected part of the cloud matter is presented in Figure 1. The initial magnetic field was of a quadrupole-like type. The shape of the ejected part of the envelope shows that matter is ejected in different directions, while the strongest ejection is near the equatorial plane. These simulations show that after the amplification of the toroidal magnetic field, the increased pressure of the magnetic field produces a MHD shock, which ejects about 7% of the mass and 3.3% of the energy of the cloud.

The application of the dipole-like initial magnetic poloidal field leads to the formation of the ejection, which mainly develops along the rotational axis (Bisnovatyi-Kogan, Ardeljan, & Moiseenko 2001). This can be clearly seen from the density distribution in Figure 2 at the developed stage of the ejection.

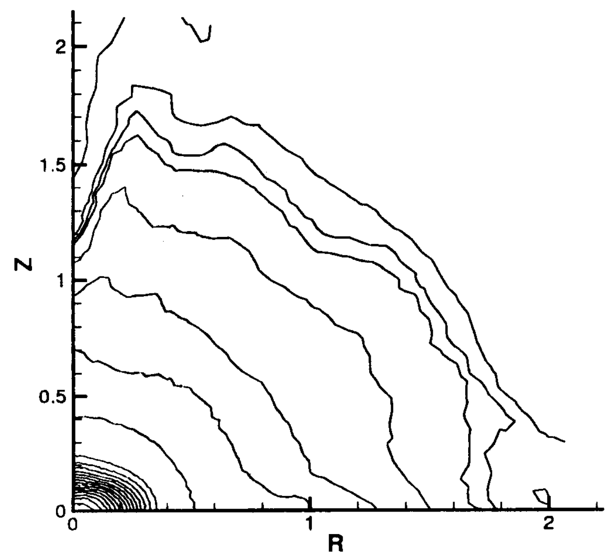

Fig. 2. The density field in a cloud collapse simulation with an initial dipole-like poloidal magnetic field at the developed stage of the ejection.

3. CORE COLLAPSE AND FORMATION OF THE ROTATING NEUTRON STAR

We have carried out simulations of the collapse of the initially rigidly rotating white dwarf and formation of the presupernova. About 6000 grid points were used. The initial conditions, the equation of state and formulae for the neutrino losses were the same as in Ardeljan et al. (1987). In the above-mentioned paper the number of grid points was less than 300 and grid reconstruction was not used. The collapse was simulated only to the stage of the maximal contraction. The application of the grid reconstruction procedure allowed us to follow the evolution of the collapsing star much further. Nevertheless, the maximal density at the first contraction stage was pretty close to that achieved by Ardeljan et al. (1987), $\rho_{\max} \approx 10^{5.4}$. The density over the model changes from the maximal value $10^{5.4}$ up to 10^{-11} in non-dimensional variables (Figure 3*a*). The simulation of a problem with such a large variation of the parameters requires application of the adaptive grid. The grid reconstruction procedure allows us not only to avoid Lagrangian grid distortion, but also to adapt the triangular grid dynamically to resolve the central parts of the core of the star (Figure 3*b*)

After the first contraction the central, dense core starts to rotate very fast due to angular momentum conservation; the shock is formed at the periphery of

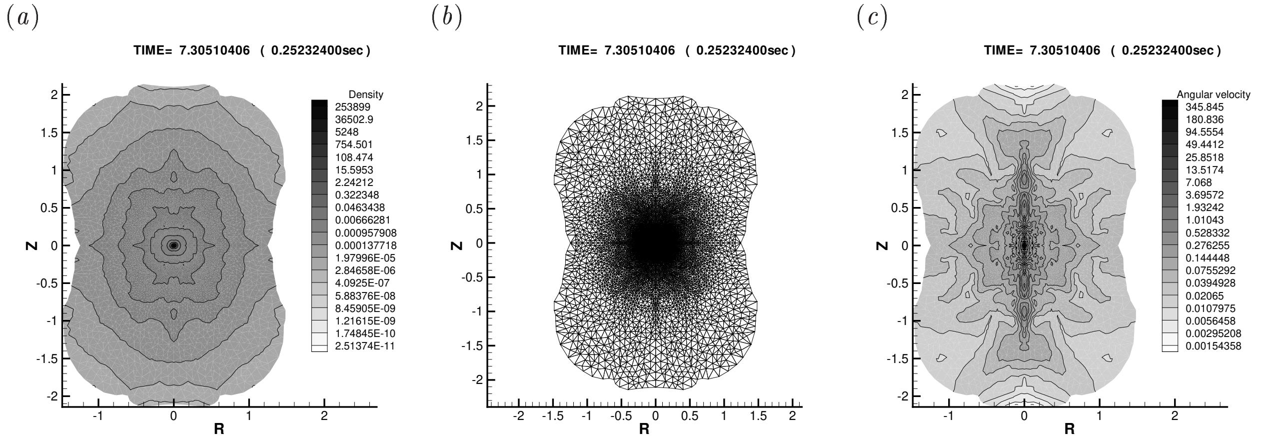

Fig. 3. Results from simulation of the collapse of a white dwarf. (*a*) The density field. (*b*) The triangular grid. (*c*) The distribution of the angular velocity.

the core. After some oscillations of the core, the star consists of the rapidly rotating compact dense core and a slowly rotating light envelope (Figure 3*c*). The details of this simulation will be published elsewhere.

The protoneutron star resulting from the collapse of the white dwarf had much stronger differential rotation than the configuration obtained after the collapse of the uniform cloud. In such a situation, the inclusion of a relatively weak initial poloidal magnetic filed could lead to the amplification of its toroidal component. At the moment when the force produced by the toroidal magnetic field becomes comparable with the gradient of the gas pressure and the gravitational force, the compression wave appears. It moves along the steeply decreasing density profile and in a short time transforms into a strong MHD shock. This shock can eject part of the envelope of the star and can produce a supernova explosion. The central core of the star should lose a significant part of its rotational energy, which is transformed to radial kinetic energy (energy of explosion).

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