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Numerical simulations of collapsars with neutrino heating and magnetic field(*)

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Summary. — Two-dimensional magnetohydrodynamic simulations are performed using the ZEUS-2D code to investigate the dynamics of a collapsar that generates a GRB jet, taking account of realistic equation of state, neutrino cooling and heating processes, magnetic fields, and gravitational force from the central black hole and self-gravity. It is found that neutrino heating processes are not so efficient to launch a jet in this study. It is also found that a jet is launched mainly by B_ϕ fields that are amplified by the winding-up effect. However, since the ratio of total energy relative to the rest mass energy in the jet is not so high as several hundred, we conclude that the jets seen in this study are not GRB jets. This result suggests that general relativistic effects, which are not included in this study, will be important to generate a GRB jet.

PACS 98.70.Rz – γ-ray sources; γ-ray bursts.

1. – Introduction

There has been growing evidence linking long Gamma-Ray Bursts (GRBs; in this study, we consider only long GRBs, so we refer to long GRBs as GRBs hereafter for simplicity) to the death of massive stars. For example, direct evidence of some GRBs accompanied by supernovae has been reported such as the association of GRB 980425 with SN 1998bw, that of GRB 030329 with SN 2003dh.

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It should be noted that these supernovae are categorized as a new type of supernovae with large kinetic energy ($\sim 10^{52}$ ergs), nickel mass ($\sim 0.5 M_\odot$), and luminosity, so these supernovae are sometimes called hypernovae. The total explosion energy of the order of 10^{52} erg is too important to be emphasized, because it is generally considered that a normal core-collapse supernova cannot cause such an energetic explosion. Thus another scenario has to be considered to explain the system of a GRB associated with a hypernova.

One of the most promising scenarios is the collapsar scenario. In the collapsar scenario, a black hole is formed as a result of gravitational collapse. Also, rotation of the progenitor plays an essential role. Due to the rotation, an accretion disk is formed around the equatorial plane. On the other hand, the matter around the rotation axis freely falls into the black hole. MacFadyen and Woosley [1] pointed out that the jet-induced explosion along the rotation axis may occur due to the heating through pair annihilation of neutrino and anti-neutrino that are emitted from the accretion disk. It was also pointed out that effects of magnetic fields and rotation may play an important role to launch the GRB jets [2,3], although neutrino heating effects are not included in their works. Recently, Rockefeller *et al.* [4] presented 3-dimensional simulations of collapsars with smoothed particle hydrodynamics code. In their study, 3-flavor flux-limited diffusion package is used to take into account neutrino cooling and absorption of electron-type neutrinos, although neutrino anti-neutrino pair annihilation is not included. They have shown that alpha-viscosity drives energetic explosion through 3-dimensional instabilities and angular-momentum transfer, although the jet is not launched and magnetic fields (source of the viscosity) are not included in their study. Thus it is not clear which effects are most important to launch a GRB jet, that is, what process is essential as the central engine of GRBs.

In this study, we have performed two-dimensional magnetohydrodynamic simulations of collapsars with magnetic fields, rotation, and neutrino cooling/heating processes. In our simulations, the realistic Equation Of State (EOS) of Blinnikov *et al.* [5] and effects of photo-disintegration of nuclei are also included. We investigated the influence of magnetic fields on the dynamics of collapsars by changing the initial amplitude of the magnetic fields.

2. – Method of calculation

The calculated region corresponds to a quarter of the meridian plane under the assumption of axisymmetry and equatorial symmetry. The spherical mesh with $150(r) \times 30(\theta)$ grid points is used for all the computations. The radial grid is nonuniform, extending from $r = 1.0 \times 10^6$ to 1.0×10^{10} cm with finer grids near the center, while the polar grid is uniform.

The basic equations in the following form are finite differenced on the spherical coordinates:

$$\frac{\mathrm{D}\rho}{\mathrm{D}t} = -\rho \nabla \cdot \mathbf{v}, \tag{1}$$

$$\rho \frac{\mathrm{D}\mathbf{v}}{\mathrm{D}t} = -\nabla p - \rho \nabla (\Phi_p + \Phi_s) + \frac{1}{4\pi} (\nabla \times \mathbf{B}) \times \mathbf{B}, \tag{2}$$

$$\rho \frac{\mathrm{D}}{\mathrm{D}t} \left(\frac{e}{\rho} \right) = -p \nabla \cdot \mathbf{v} - \mathbf{L}_\nu^- + \mathbf{L}_\nu^+ + \mathbf{L}_{\mathrm{nucl}}, \tag{3}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}), \tag{4}$$

$$\Delta \Phi_s = 4\pi G \rho, \tag{5}$$

$$\frac{\mathrm{D}Y_e}{\mathrm{D}t} = -Y_p \Gamma_{p\rightarrow n} + Y_n \Gamma_{n \rightarrow p}, \tag{6}$$

where ρ, $\mathbf{v}$, p, Φ_p, Φ_s e, $L_\nu^\pm$, $L_{\rm nucl}$, Y_e, Y_p, Y_n, $\Gamma_{p\rightarrow n}$, and $\Gamma_{n\rightarrow p}$, and are density, velocity, pressure, gravitational potential due to the central point mass (black hole), gravitational potential due to self-gravity, internal energy density, heating/cooling rates due to neutrino processes, energy gain (loss) rate due to nuclear reaction, fraction of electron, proton, neutron, and reaction rate from proton to neutron (electron capture rate plus ν_e capture on neutron) and from neutron to proton (positron capture plus $\bar{\nu}_e$ capture on proton), respectively.

We adopt the model E25 in Heger *et al.* [6]. This model corresponds to a star that has $25M_\odot$ initially with solar metallicity, but loses its mass and becomes to be $5.45M_\odot$ of a Wolf-Rayet star at the final stage.

In this study we choose a simple form for the initial configuration prior to collapse and the amplitude is changed parametrically. Initial configuration of the magnetic fields is chosen as follows:

$$\vec{B}(\vec{r}) = \frac{1}{3} B_0 \left(\frac{r_0}{r}\right)^3 (2\cos\theta \vec{e_r} + \sin\theta \vec{e_\theta}) \quad \text{for } r \geq r_0 \tag{7}$$

$$= \frac{2}{3} B_0 (\cos\theta \vec{e_r} - \sin\theta \vec{e_\theta}) \quad \text{for } r < r_0. \tag{8}$$

This configuration represents that the magnetic fields are uniform in a sphere ($r < r_0$), while dipole at the outside of the sphere. We set r_0 to be the boundary between CO core/He layer ($= 3.6 \times 10^9$ cm). B_0 corresponds to the strength of the magnetic field in the sphere. We have chosen B_0 to be 0 and 10^9G.

3. – Results

We show in fig. 1 the density contour of the central region of the progenitor ($r \leq 10^8$cm) with velocity fields for model 0 (= no magnetic field) and model 9 (= with magnetic field). In the top panels, density contour with velocity fields for model 0 at $t = 2.1$ s (left panel) and $t = 2.2$ s (right panel) is shown, while in the bottom panels the ones for model 9 is shown. The color online represents the density (g cm^{-3}) in logarithmic scale (10^3–10^{12}). Vertical axis and horizontal axis represent polar axis (= rotation axis) and equatorial plane, respectively. You can easily find that a jet is launched at $t = 2.1$ s for model 9, while no jet occurs for model 0.

However, the ratio of total energy relative to the rest mass energy in the jet at the final stage of simulations for model 9 suggests that the bulk Lorentz factor of the jet will not reach as high as several hundreds, so we conclude the jet seen in this study will not be a GRB jet. Further analysis is written in Nagataki *et al.* [7].

4. – Conclusion

We have found that neutrino heating processes (neutrino and anti-neutrino pair annihilation, and ν_e and $\bar{\nu}_e$ captures on free nucleons) are not so efficient to launch a jet.

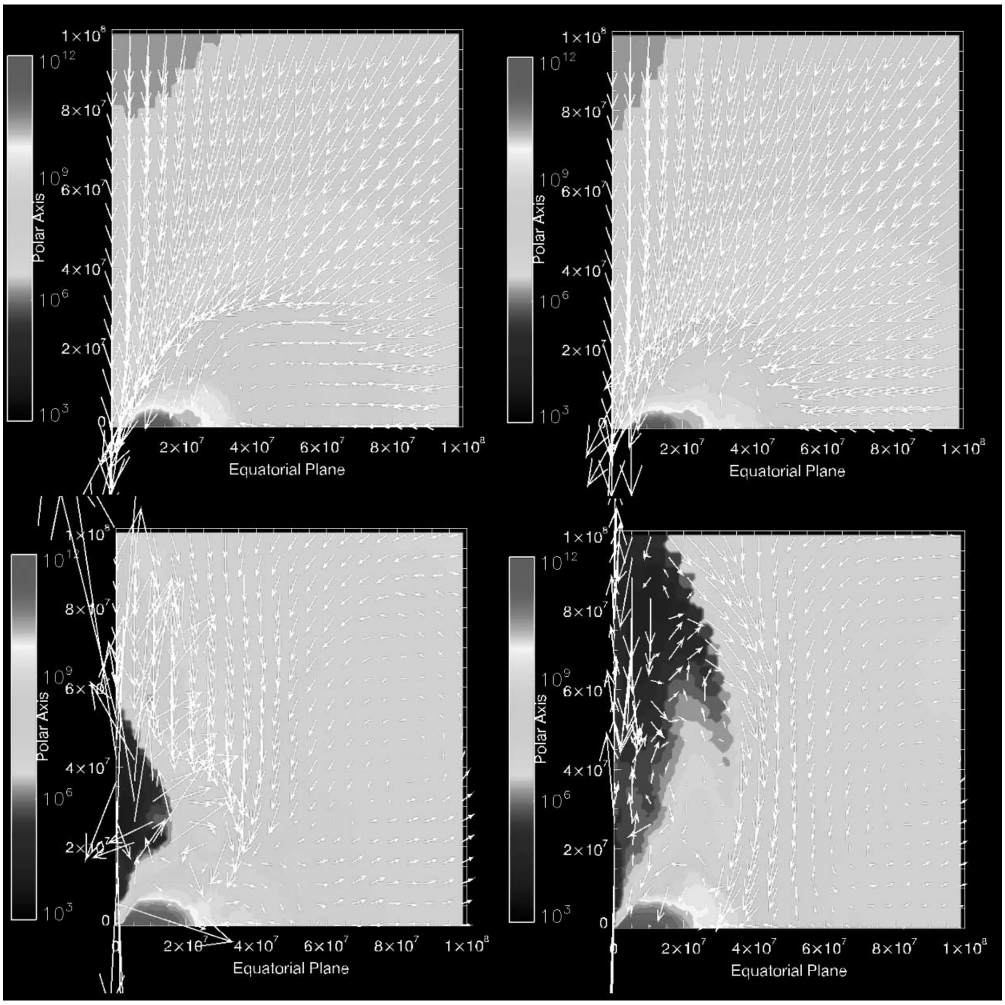

Fig. 1. – Top panels: density contour with velocity fields for model 0 at $t = 2.1$ s (left panel) and $t = 2.2$ s (right panel). Bottom panels: same with upper panels, but for model 9. The color represents the density (g cm^{-3}) in logarithmic scale (10^3–10^{12}). In this figure, the central region of the progenitor ($r \leq 10^8$cm) is shown. Vertical axis and horizontal axis represent rotation axis and equatorial plane, respectively.

We have found that a jet is launched by magnetic fields (in particular, B_ϕ fields that are amplified by the winding-up effect).

Although the jet is seen in model 9, the ratio of total energy relative to the rest mass energy in the jet at the final stage of simulations for model 9 suggests that the bulk Lorentz factor of the jet will not reach to as high as several hundreds, so we conclude the jet seen in this study will not be a GRB jet.

Since GRB jets are not obtained in this study, we consider that general relativistic effects, by which the efficiency of energy deposition through weak interactions will be enhanced and rotation energy of the black hole will be transfered to matter through the magnetic fields, will be important to generate a GRB jet. Thus we are planning to develop a general relativistic magnetohydrodynamics code in the very near future.

Discussion

There were several questions for my talk at Venice conference.

1) Neutrino heating and cooling should be important for shorter duration GRBs. Because this is not observed for long duration GRBs, can we conclude that neutrino processes are not important for long duration GRBs?
2) Why is jet not created without magnetic field?
3) What is the mechanism of jet generation with magnetic field?

I think the question 1) is really important. In fact, I wrote a paper in which the mass accretion rate should correlate with the neutrino density at the central region, which means that the duration of the long duration GRB should correlate with the explosion energy as long as the neutrino processes are important for the mechanism of long GRBs (Nagataki *et al.*, *Astropart. Phys.*, **18** (2003) 551). But it should be also noted that the neutrino density will be saturated if the mass accretion rate becomes larger than a critical value where the matter density becomes optically thick against neutrinos. In such a case, the duration of long GRBs may not be correlated with the explosion energy of GRBs. So we think that more realistic and precise numerical simulation will be required to derive a firm conclusion on the correlation. As for the question 2), we think neutrino heating effect is not so effective to drive a jet in this study. However, as stated in this manuscript, the heating effect may be enhanced if we take into accout the general relativistic effect. So further study is required to derive a firm conclusion on the effect of neutrino heating. As for the question 3), mainly B_ϕ, which is amplified by winding-up effect, drives the jet.

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