Gamma-Ray Burst Physics

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Abstract. I have developed two-dimensional general relativistic magnetohydrodynamic (GRMHD) code. I have performed numerical simulations of collapsars using these codes and realistic progenitor models. In the GRMHD simulation, it is shown that a jet is launched from the center of the progenitor. We also performed simulations of collapsars with different Kerr parameters $a = 0, 0.5, 0.9, 0.95$. It is shown that a more rapidly rotating black hole is driving a more energetic jet. No jet is seen for the case of Schwartzschild black hole case, while the total energy of the jet is as large as $10^{50}$ erg for a rapidly rotating Kerr black hole case ($a = 0.95$). In order to explain the high luminosity of a GRB, it is concluded that a rapidly rotating black hole is favored (‘faster is better’). We also performed two-dimensional hydrodynamic simulations in the context of collapsar model to investigate the explosive nucleosynthesis happened there. It is found that the amount of $^{56}$Ni is very sensitive to the energy deposition rate. This result means that the amount of synthesized $^{56}$Ni can be little even if the total explosion energy is as large as $10^{52}$ erg. Thus, some GRBs can associate with faint supernovae. Thus we consider it is quite natural to detect no underlying supernova in some X-ray afterglows.

1. Introduction

Gamma-Ray Bursts (GRBs; in this study, we consider only long GRBs, so we refer to long GRBs as GRBs hereafter) have been mysterious phenomena since their discovery in 1969. Last decade, observational evidence for supernovae (SNe) and GRBs association has been reported. Some of the SNe that associate with GRBs were very energetic and blight. The estimated explosion energy was of the order $10^{52}$ ergs, and produced nickel mass was about $0.5 M_\odot$. Thus they are categorized as a new type of SNe (sometimes called as hypernovae). The largeness of the explosion energy is very important, because it can not be explained by the standard core-collapse SN scenario, and other mechanism should be working at the center of the progenitors. In this paper, we investigate the dynamics of collapsars using two-dimensional general relativistic magnetohydrodynamic (GRMHD) code[1].

Also, we perform two-dimensional hydrodynamic simulations in the context of collapsar model to investigate the explosive nucleosynthesis happened there. We have to be careful to the point that where and when $^{56}$Ni is synthesized in the collapsar is not unclear. This is because the explosion mechanism is not known well. One possibility is that $^{56}$Ni is synthesized in the jet region like jet-like supernova explosion[2, 3]. Another possibility is that nucleosynthesis in the accretion disk, and some fraction of the accreting matter escape from the system[4]. In this paper, we consider the former possibility.
2. GENERAL RELATIVISTIC MHD SIMULATIONS

2.1. Formulation

We have adopted a conservative, shock-capturing scheme with Harten, Lax, and van Leer (HLL) flux term with flux-interpolated constrained transport technique. We use a third-order Total Variation Diminishing (TVD) Runge-Kutta method for evolution in time, while monotonized central slope-limited linear interpolation method is used for second-order accuracy in space. 2D scheme (2-dimensional Newton-Raphson method) is usually adopted for transforming conserved variables to primitive variables.

When we perform simulations of GRMHD, Modified Kerr-Schild coordinate is basically adopted with mass of the BH (M) fixed. We use $G = M = c = 1$ unit. The calculated region covers from $r = 1.8$ to $3 \times 10^4$ (that corresponds to 5.3 $\times 10^5$ cm and 8.9 $\times 10^9$ cm in cgs units). We adopt the model 12TJ in Woosley and Heger (2006)[5]. We set the Kerr-parameter of the black hole at the center is set to be 0.5 throughout of the simulation. The initial, weak poloidal magnetic fields are put initially. The minimum plasma beta in the simulation region is greater than 100 initially.

2.2. Results

Figure 1. Contours of rest mass density at the central region in logarithmic scale at $t = 180000$ (that corresponds to 1.773 sec), in which cgs units are used assuming that the gravitational mass of the BH is $2 M_\odot$. The length unit in the vertical/horizontal axes corresponds to 2.95 times $10^7$ cm.

Figure 2. Contour of the plasma beta ($p_{\text{gas}}/p_{\text{mag}}$) at $t = 180000$ in logarithmic scale.

In Figure 1, contours of rest mass density at the central region are shown. Contours represent the density in units of g cm$^{-3}$ in logarithmic scale. The length $r = 200$ corresponds to 5.9 times $10^7$ cm. The time unit corresponds to 9.85 times $10^{-6}$ sec. Figure 2 shows contours of the plasma beta ($p_{\text{gas}}/p_{\text{mag}}$) in logarithmic scale at $t = 180000$. As expected, the plasma beta is low in the jet region while it is high in the accretion disk region.

3. Dependence on the Kerr Parameter

Next, we studied the dependence of dynamics on the Kerr Parameter. The initial condition is also same with the previous section, but for different Kerr Parameters. In the previous section,
the Kerr parameter, \( a \), was assumed to be 0.5, but in this study we perform simulations for \( a = 0, 0.5, 0.9, 0.95 \), respectively (we name them as Model A, B, C, D, respectively).

In Figure 3, contours of rest mass density in logarithmic scale for all models at the same time-slice \( t = 160000 \) (that corresponds to 1.5760 sec) are shown. Cgs units are used for the rest mass density, while the length in the vertical/horizontal axes is written in \( G = M = c = 1 \) unit. \( r = 1 \) and 4000 corresponds to \( 2.95 \times 10^5 \) cm and \( 1.18 \times 10^9 \) cm, respectively. These results are projected on the \((r \sin \theta, r \cos \theta)\)-plane. Upper left panel shows the state of Model A \((a = 0)\), upper right panel shows the one of Model B \((a = 0.5)\), lower left panel shows the one of Model C \((a = 0.9)\), and lower right panel shows the one of Model D \((a = 0.95)\). It is clearly shown that the rotating black hole drives the jet (the Schwarzschild black hole cannot drive a jet (Model A), while a more rapidly rotating black hole is driving a stronger jet).

**Figure 3.** Contours of rest mass density in logarithmic scale for all models at the same time-slice \( t = 160000 \) (that corresponds to 1.5760 sec). Cgs units are used for the rest mass density, while the length in the vertical/horizontal axes is written in \( G = M = c = 1 \) unit. \( r = 1 \) and 4000 corresponds to \( 2.95 \times 10^5 \) cm and \( 1.18 \times 10^9 \) cm, respectively. These results are projected on the \((r \sin \theta, r \cos \theta)\)-plane. Upper left panel shows the state of Model A \((a = 0)\), upper right panel shows the one of Model B \((a = 0.5)\), lower left panel shows the one of Model C \((a = 0.9)\), and lower right panel shows the one of Model D \((a = 0.95)\).

In Figure 4, plots of the jet energy for all models at \( t = 160000 \) are shown. The definition of the jet energy is:

\[
E_{\text{Jet}} = 2 \times 2\pi \int_{r \infty}^{r_+} dr \int_{0}^{\theta} d\theta \sqrt{-g(T^t_t - \rho u^0 u_0)},
\]

where \( T^t_t \) is the \((t, t)\) component of total energy-momentum tensor and integration is done only for the region where \( u^r \) (radial component of 4-velocity of fluid) is positive. It is noted that the contribution of the rest mass energy is subtracted. Factor 2 is coming from the symmetry of the system with respect to the equatorial plane. Dot curve represents the jet energy within the opening angle \( \theta = 5^\circ \), while dashed curve represents the one within \( \theta = 10^\circ \). The unit of vertical
axis is $10^{48}$ erg. It is clearly seen that a more rapidly rotating black hole is driving a stronger jet. The total energy of the jet for Model D ($a = 0.95$) is as large as $10^{50}$ erg.

![Figure 4. Plots of the jet energy (see text for the definition in detail) for all models at $t = 160000$ (that corresponds to 1.5760 sec). The unit of vertical axis is $10^{48}$ erg. Dot curve represents the jet energy within the opening angle $\theta = 5^\circ$, while dashed curve represents the one within $\theta = 10^\circ$.]

4. EXPLOSIVE NUCLEOSYNTHESIS IN COLAPSAR

4.1. Formulation

We have done two-dimensional hydrodynamic simulations taking into account self-gravity and the gravitational potential of the central point mass. The calculated region corresponds to a quarter of the meridian plane under the assumption of axisymmetry and equatorial symmetry. The spherical mesh with 250 by 30 grid points is used for all the computations. The radial grid is nonuniform, extending from $2 \times 10^7$ to $3 \times 10^{11}$ cm with finer grids near the center, while the polar grid is uniform. We adopt the collapsar model of MacFadyen & Woosley (1999)[4].

To simulate the jet-induced explosion, we deposit only thermal energy at a rate $10^{51}$ ergs/s homogeneously within a 30 degree cone around the rotation axis for 10 sec. We name this model E51. For comparison, we perform a calculation in which total explosion energy ($10^{52}$ ergs) is put initially with the same deposition region as model E51. We name these models E52.

Since the chemical composition behind the shock wave is not in nuclear statistical equilibrium, the explosive nucleosynthesis has to be calculated using the time evolution of density and temperature, and a nuclear reaction network, which is called post-processing. The nuclear reaction network contains 250 species[6, 7].

4.2. Results

We deposited thermal energy to launch a jet from the central region of the collapsar. The density structure for models E51 shows a sharp, narrow jet propagates along the rotation axis in model E51. On the other hand, in the case of E52, a broad, deformed shock wave propagates in the progenitor (see also Nagataki et al. (2006)[3].
Positions of the ejected test particles at 0 sec that meet the condition that the mass fraction of $^{56}$Ni becomes greater than 0.3 as a result of explosive nucleosynthesis for model E51. The total ejected mass of $^{56}$Ni is 0.0439 $M_\odot$.

In Figure 5, positions of the ejected test particles for model E51 at 0 sec are shown that satisfy the condition that the mass fraction of $^{56}$Ni becomes greater than 0.3 as a result of explosive nucleosynthesis. The total ejected mass of $^{56}$Ni becomes 0.0439 $M_\odot$, which is much smaller than the observed values of hypernovae. In Figure 6, the same values are shown as in Figure 5, but for models E52. The total ejected mass of $^{56}$Ni is 0.23 $M_\odot$, which is comparable to the observed values of hypernovae.

Thus we can conclude that the resulting amount of $^{56}$Ni is very sensitive to the energy deposition rate. This result means that the amount of synthesized $^{56}$Ni can be little even if the total explosion energy is as large as $10^{54}$ erg. Thus, some GRBs can associate with faint supernovae. Thus we consider it is quite natural to detect no underlying supernova in some X-ray afterglows such as GRB060614.

**5. Summary and Conclusion**

I have performed numerical simulations of collapsars using these codes and realistic progenitor models. In the GRMHD simulation, it is shown that a jet is launched from the center of the progenitor. We also performed simulations of collapsars with different Kerr parameters $a = 0, 0.5, 0.9, 0.95$. It is shown that a more rapidly rotating black hole is driving a more energetic jet. No jet is seen for the case of Schwarzschild black hole case, while the total energy of the jet is as large as $10^{50}$ erg for a rapidly rotating Kerr black hole case ($a = 0.95$). In order to explain the high luminosity of a GRB, it is concluded that a rapidly rotating black hole is favored (‘faster is better’). We also performed two-dimensional hydrodynamic simulations in the context of collapsar model to investigate the explosive nucleosynthesis happened there. It is found that the amount of $^{56}$Ni is very sensitive to the energy deposition rate. This result means that the amount of synthesized $^{56}$Ni can be little even if the total explosion energy is as large as $10^{52}$ erg. Thus, some GRBs can associate with faint supernovae. Thus we consider it is quite natural to
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References
[1] S. Nagataki, Astrophys. J. 704 (2009) 937.
[2] S. Nagataki, A. Mizuta, S. Yamada, H. Takabe, K. Sato, Astrophys. J. 596 (2003) 401.
[3] S. Nagataki, A. Mizuta, K. Sato, Astrophys. J. 647 (2006) 1255.
[4] A. I. MacFadyen, S. E. Woosley, Astrophys. J. 524 (1999) 262.
[5] S. E. Woosley, A. Heger Astrophys. J. 637 (2006) 914.
[6] S. Nagataki, M. Hashimoto, K. Sato, S. Yamada, Astrophys. J. 486 (1997) 1026.
[7] S. Nagataki, Astrophys. J. Suppl. 127 (2000) 141.