General Relativistic MHD Simulations of the Gravitational Collapse of a Rotating Star with Magnetic Field as a Model of Gamma-Ray Bursts

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Abstract

We have performed 2.5-dimensional general relativistic MHD simulations of the gravitational collapse of a rotating massive star with magnetic field as a model of gamma ray bursts (GRBs). This simulation showed the generation of jet-like-outflow from the gravitational collapse. We found the jet is accelerated by the gradient force of gas pressure and the centrifugal force and is collimated by the pinching force of toroidal magnetic field and the effect of geometry of magnetic field.

1. Introduction

Gamma ray bursts (GRBs) and the afterglows are well described by the fireball model, in which a relativistic outflow is generated from a compact central engine [8]. The rapid temporal decay of several afterglows is consistent with the evolution of a highly relativistic jet. Therefore, formation of the relativistic jets with bulk Lorentz factors $\sim 10^2 - 10^3$ from compact central engine represents a major problem in the GRB models.

From recent observations, some evidence was found of the connection between GRBs and supernova. This evidence includes the association of GRBs with star forming regions [2], "Bump" feature which resembles the light curves of Type 1 supernovae in the optical afterglows of several GRBs [3], and association of GRB980425-SN1998bw [4] and GRB030329-SN2003df. It is probable that at least major subclass of GRBs is the consequence of the supernova.

In previous works, the effect of stellar rotation and intrinsic magnetic field on the gravitationally collapse of massive stars was numerically studied [6,7]. The simulations showed the formation of two oppositely jets ejected from the collapsed core. We think it is possible to apply as the model of central engine of GRBs to

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create the relativistic jets.

In this study, we perform 2.5-dimensional general relativistic MHD simulations of the gravitational collapse of a rotating star with magnetic field. We investigate the physics around the formation of jets, the acceleration force on the jets, and the dependence upon the acceleration of jets on the initial magnetic field strengths and on the initial rotational velocity of stellar component.

2. Numerical Method

In order to study the formation of relativistic jets from supernova, we use 2.5-dimensional general relativistic magnetohydrodynamics (GRMHD) code [5]. We neglect self-gravity, neutrino transport, and nuclear burning in this simulation.

We assume following situation as the initial condition of our simulation. A few $M_\odot$ stellar mass black hole is produced in the center of stellar remnant as a result of iron core collapse and accretion of stellar matter, the weak shock launches in a few hundred km, and the post-shocked gas falls back toward the central black hole. We consider a non-rotating black hole as the central black hole, and assume that the gravitational potential is fixed in time. We use the data of 1-dimentional gravitational collapse simulation for the initial density, pressure and radial velocity distribution [8]. We input the effect of stellar rotation and intrinsic magnetic field in our simulation. The initial toroidal velocity distribution is a function of radius only: $v_\phi = v_0(R^2/(r^2+R^2))r$. Here, $R = 100r_s$ (r_s is Schwartzchild radius) and v_0 is the parameter of rotation velocity. The initial magnetic field is assumed to be uniform and parallel to the rotational axis. It is Wald solution for a non-rotating black hole: $B_r = B_0 \cos\theta, B_\theta = -\alpha B_0 \sin\theta$. Here, B_0 is the parameter of magnetic field strength.

The simulation is performed in the region $2.0r_s \leq r \leq 60r_s$, $0 \leq \theta \leq \pi/2$, with 120×120 mesh points. We assume axisymmetry with respect to z-axis and mirror symmetry with respect to the equatorial plane. We employ a free boundary condition at $r = 2.0r_s$ and $r = 60r_s$.

3. Results

3.1. Formation of Jets

The stellar matter that was initially ejected owing to the weak outgoing shock begins to fall into the central black hole because of the gravity of the central black hole. This collapse is anisotropic through the effect of rotation and magnetic field. The accreting matter piles up on the equatorial plane. Therefore the disk-like structure is formed near the central black hole. The magnetic field is frozen into the plasma so that it is dragged and twisted by the accreting matter. The amplified toroidal magnetic field deceralate the accreting stellar matter and make a shock wave. The shock wave propagates outward with twisted magnetic field

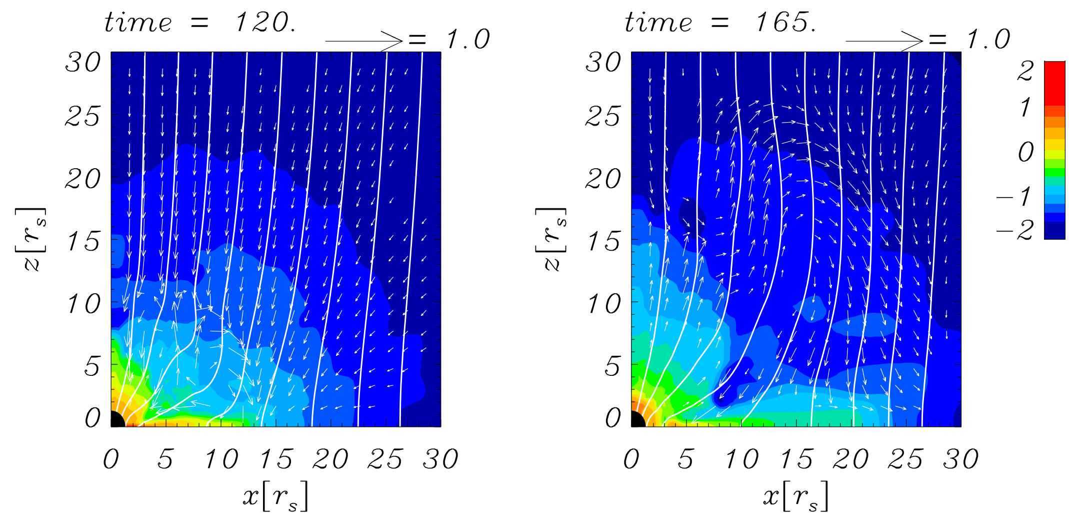

Fig. 1. Density structure at t=120 τ_s(left) and t=165 τ_s(right). The unit of time τ_s is r_s/c. The white vertical lines are the magnetic field. Arrows shows the poliodal velocity vectors normalized by the light speed.

and makes jet-like outflow.

The jet-like outflow is generated behind the shock wave. The shock wave has the high gas pressure gradient force and high centrifugal force. These forces push back the accreting stellar matter and construct the jet. Therefore, we understand that the jet is generated and accelerated by the gas pressure gradient and the centrifugal forces.

3.2. Properties of Jets

The velocity of jet formed in this simulation is about 0.4c. The magnetic twist is large in the jet-forming region. Toroidal velocity is larger than poloidal velocity in the jet-forming region. Therefore, the jet has helical structure.

The magnetic field plays important role in collimation. The shock wave propagates upward with the twisted toroidal magnetic field. The outflow becomes jet through the pinching force of toroidal magnetic field and the effect of geometry of magnetic field. Therefore we understand the collimation of jet is produced by the magnetic field.

3.3. Dependence on initial magnetic field strength and rotatinal velocity

We examine the dependence on these physical quantities of jet on the initial magnetic field strength and initial rotational velocity of stellar matter. When initial magnetic field strength becomes strong, the velocity of jet becomes slow and the twist of magnetic field becomes weak. The jet is generated by the shock. Thus, the velocity of jet is related to the strength of shock. In order to make strong shock, the magnetic field has to be twisted significantly and store enough magnetic energy. When initial magnetic field is strong, the magnetic field cannot be twisted significantly because Alfven wave propagates as soon as the magnetic field is twisted. Therefore, the velocity of jet becomes slow and the twist of magnetic field becomes weak.

When initial rotational velocity of stellar matter is fast, the velocity of jet becomes fast but it tends to constant at some limit values. In this case, the magnetic field is twisted significantly and stores enough energy and it makes fast jet. However the stored magnetic energy has limit values. It is determined by the balance between the propagation time of Alfven wave and the relation time of the disk (i.e. twisting time). Therefore, it is means that the magnetic field strength determines the maximum velocity of jet.

4. Discussion

We show the generation of jet from gravitational collapse of rotating star with intrinsic magnetic field by using the 2.5D general relativistic MHD simulation code. The velocity of jet is about $0.4c$. It is too slow to be applied to the jet of GRBs. We have to consider other acceleration mechanism. The break out of stellar surface is the most applicable acceleration mechanism of outflow from gravitational collapse. When the jet goes through the stellar surface, the strong gradient of density accelerates the jet. In previous works, it was numerically studied [1,9]. The simulations showed the significant acceleration of jet and the terminal Lorentz factor is $\Gamma \sim 50$. However, they use the relativistic hydrodynamics code. Their simulation has the problem of jet collimation. The magnetic field plays important role in collimation. We will try to simulate the propagation of jet outside the stellar surface by using the GRMHD code.

5. References

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