Relativistic Jet Propagation and Dynamics in Massive Progenitor and ISM of GRBs

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We investigate the propagation of the jet in the progenitor using two dimensional relativistic hydrodynamic simulations. The scenario of the collapasr as the central engine of the gamma-ray burst requests that a collimated outflow should emerge from the center of the core to be observed as a gamma-ray burst later. Several types of jets are studied to see what type of the outflow from the center can propagate in the progenitor keeping collimated structure and break out the surface of the progenitor. The relativistic flow with the bulk Lorentz factor is 5 can propagate and break out of the progenitor. After the eruption, high velocity component survives along the cylindrical axis. The hot jet can tunnel into the progenitor converting its thermal energy into kinetic energy. The cold and slow ($v = 0.3c$) jet model does not collimate and expands where the jet is injected.

1. INTRODUCTION

Recent observations of gamma-ray bursts (GRBs) associated with supernovae (SNe), for example, GRB980425/SN1998bw [Galama et al. 1998] and GRB030329/SN2003dh [Hjorth et al. 2003, Price et al. 2003, Stanek et al. 2003, Uemura et al. 2003], are one of the strong evidences that the origin of the GRBs are SNe. A model of the collapsar which is a death of a massive star at the last stage of the stellar evolution was proposed by MacFadyen and Woosley [1999], Woosley [1993] as a central engine of GRBs. When the iron core is collapsed, a system of a black hole or proto-neutron star and accretion disk is formed in the center of the progenitor. Then outer envelopes begin a free fall. Some fraction of the collapsing gas becomes outflow from the system of the central object and accretion disk. Since the time scale of the free fall of envelopes is longer than the dynamical time scale of the crossing jet. After the formation of the outflow the flow should propagate in the progenitor and break through the surface of the progenitor into interstellar medium. Finally the outflow is observed as GRBs and afterglows.

The dynamics of the jet into some ambient gas is essentially multidimensional phenomena as well known in the numerical simulations of the propagation of AGN jets (for example Mizuta et al. [2004], also see references therein). Some numerical relativistic hydrodynamic simulations have been done in the context of collapsar's model. Aloy et al. [2000] included relativistic effect in the model by MacFadyen and Woosley [1999]. They performed relativistic hydrodynamic simulations depositing thermal energy around the center of the progenitor assuming that the iron core has been collapsed. Their initial mass density profile is very flattened due to rotation of the progenitor. The deposited energy expands and forms very collimated outflow, namely a "jet". They got maximum Lorentz factor of the outflow about 40 when the jet breaks. Zhang et al. [2003, 2004] showed some numerical simulations of the jet propagation in the progenitor and after breaking out from the progenitor. Their model is mainly very hot jet. Injected jets from the boundary always propagate in the progenitor keeping good collimation.

The formation mechanism of the outflow from the center of the progenitor is not understood yet. Thermal deposition around the core in the models by Aloy et al. [2000], MacFadyen and Woosley [1999] was assumed that the annihilation of neutrino and anti-neutrino occurs there. MHD model (for example, Mizuno et al. [2004], Proga et al. [2003]) is still fascinating for the formation of the jet from the system of a compact object and accretion disk. The question where the acceleration to relativistic regime happens is also still open question on the GRBs, since observed features of GRBs requres relativistic outflow in which bulk Lorentz factor is a few hundreds.

We performed several numerical simulations on the jet propagation in the progenitor and ISM to help us to explore the formation mechanism of the outflow around the center of the progenitor. We discuss what type of outflow the central system should form with wide range of parametric search of the injected jet.

2. NUMERICAL METHOD AND CONDITIONS

2.1. Hydrodynamic Equations

We numerically solve two dimensional relativistic hydrodynamic equations assuming the asxisymmetric geometry. The equations are,

$$\frac{\partial(\rho\Gamma)}{\partial t} + \frac{1}{r}\frac{\partial r(\rho\Gamma v_r)}{\partial r} + \frac{\partial(\rho\Gamma v_z)}{\partial z} = 0, \quad (1)$$

$$\frac{\partial(\rho h\Gamma^2 v_r)}{\partial t} + \frac{1}{r}\frac{\partial r(\rho h\Gamma v_r^2 + p)}{\partial r} + \frac{\partial(\rho h\Gamma^2 v_r v_z)}{\partial z} = \frac{p}{r}, \quad (2)$$

$$\frac{\partial(\rho h\Gamma^2 v_z)}{\partial t} + \frac{1}{r}\frac{\partial r(\rho h\Gamma^2 v_r v_z)}{\partial r} + \frac{\partial(\rho h\Gamma^2 v_z^2 + p)}{\partial z} = 0, \quad (3)$$

$$\frac{\partial(\rho h\Gamma^2 - p)}{\partial t} + \frac{1}{r}\frac{\partial r(\rho h\Gamma^2 v_r)}{\partial r} + \frac{\partial(\rho h\Gamma^2 v_z)}{\partial z} = 0, \quad (4)$$

where, ρ is rest mass density, p is pressure, v_i is three velocity component in i direction, Γ is Lorentz factor ($\equiv (1-v^2)^{-1/2}$), and h is specific enthalpy ($\equiv 1+\epsilon+p/\rho$), respectively. The equations are written in the unit that the speed of light is unity. The numerical hydrodynamic code used in Mizuta et al. [2004] is employed in this study. The code adopts Godunov-type scheme which is good for capturing a strong shock with a few grid points. The code is second order accuracy in space. In this study, we consider the crossing jet in the progenitor and after breaking the surface of the progenitor. Since this time scale is smaller than that of free fall, we neglect gravitational potential of the core. We also neglect self gravity. When a jet is injected from the boundary into the progenitor, a bow shock appears. Nucleosynthesis could occur in the gas driven by this strong bow shock. Since produced entropy due to the nucleosynthesis is much smaller than that by strong shock jumps, we do not consider energy sources in the energy equation (Eq. 4). We assume the ideal gas equation of state such as $p = (\gamma-1)\rho\epsilon$, where ϵ is specific internal energy, and $\gamma(= 4/3$ constant in this study) is adiabatic index, respectively.

2.2. Progenitor and Jet Conditions

It is assumed that the progenitor is spherical symmetry when the iron core is collapsed. We adopt mass profile in radial direction from the model by Hashimoto [1995]. It has about 40 solar mass in the main sequence and 16 solar mass at pre-supernovae stage. The hydrogen envelope has already been lost. Figure 1 shows the mass density profile of the radial direction from the center to the surface. The inner boundary for the computation is set to be 2×10^8 cm from the center of the progenitor. This condition corresponds that about two solar mass is collapsed and forms the proto-neutron star or black hole and surrounding accretion disk system. Since the pressure becomes very high due to the strong bow shock, the pressure of the progenitor is set to be very cold initially.

A jet which is parallel to the cylindrical (z) axis is injected from the inner boundary. The radius ($R_{\rm jet}$) and power ($\dot{E}_{\rm jet}$) of the jet is fixed to $R_{\rm jet} = 7\times10^7$cm and $\dot{E}_{\rm jet} = 10^{51}$ergs sec^{-1} respectively. The energy flux ($\dot{E}_{\rm jet}/\pi R_{\rm jet}^2$) which is also fixed value is uniform, namely, it does not have any dependence of the radius. Since the explosive energy of SN1998bw and 2003dh

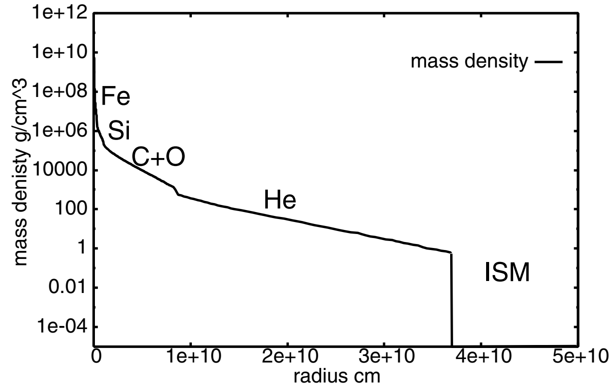

Figure 1: Mass density profile of the radial direction of the progenitor from the center of the core at pre-supernova stage. The profile $r > 2\times10^8$cm is used for the set up initial condition assuming spherical symmetry. As a result, about two solar mass has collapsed.

is about 10^{52} ergs which is higher than the normal explosive energy 10^{51} ergs [Hjorth et al. 2003, Iwamoto et al. 1998, Woosley et al. 1999], about ten second injection satisfies these explosive energies.

Another two parameters are necessary to set the jet injection. The bulk Lorentz factor and specific internal energy are chosen for this. Each parameters characterize the kinetic and thermal energy per particle of the injected jet. As the Lorentz factor and/or specific internal energy increase, the kinetic and/or thermal energy per particle increase. The rest mass density and pressure can be derived from these conditions. As the specific internal energy and/or bulk Lorentz factor increases, the rest mass density decreases. Assuming that all internal energy is converted to kinetic energy, the maximum bulk Lorentz factor is estimated from energy conservation law.

$$\Gamma_{max} \sim \Gamma_0(1+\epsilon_0/c^2), \quad (5)$$

where Γ_0 is initial bulk Lorentz factor.

We performed six sets of parameters. Those are mainly divided into two types. One is the model with initially relativistic flows ($\Gamma_0 = 5$, Faster model). The other is non-relativistic model ($v_0 = 0.3c$, Slower model). Several specific internal energy ($\epsilon_0/c^2 = 0.5, 1,$ and 5) is tested and labeled as SA, SB, SC, FA, FB, and FC (see Table I). The mass density varies from a few tens to 10^4g cm^{-3}. The mass density at the most inner region for the computation is 10^6g cm^{-3}. All our model is initially so-called "light jet". Such jet is expected to interact with the backflow [Mizuta et al. 2004] and have complex internal structures in the jet. From eq. (5), the most predominant case for the GRBs is the model FC ($\Gamma_{max} \sim 30$). Although this Lorentz factor is still smaller than required one in the GRBs, we expect that our parametric search can predict the cases with larger specific internal energy.

Table I Numerical conditions of injected jets. Each model is labeled as SA, SB, SC, FA, FB, and FC

ϵ_0/c^2 \ Γ_0 (v_0/c)	1.05(0.3)	5(0.980)
0.1	SA	FA
1.0	SB	FB
5.0	SC	FC

3. RESULTS AND DISCUSSION

3.1. Faster Models

At first, we discuss the cases of faster models (FA, FB, and FC). Figure 2 (a) shows rest mass density and Lorentz factor contour of the models FC at t=2.5 sec. It should be noted that the origin of the figure is one of the boundaries of the computational domain and does not correspond to the center of the progenitor. The bulk Lorentz factor increases in the progenitor up to about 30. This value is in good agreement with Eq. (5). Another models FA and FB also show similar dynamics, namely the flow is very collimated and maximum Lorentz factor in the jet follows Eq. (5).

The pressure inside of the bow shock is almost uniform except at the head of the jet where three discontinuities such as a bow, contact discontinuity, and reverse shock appear. At the reverse shock, the most kinetic energy is converted to thermal energy. A backflow which is unti-parallel flow to the jet can be seen. The interaction with jet and backflow enhances the appearance of the oblique shocks in the jet which help the reconfinement [Mizuta et al. 2004]. After the eruption of the surface of the progenitor, we follow the propagation of 1×10^{10} cm. An expansion occurs when the break happens. But high velocity component survives along the cylindrical axis. We will follow the propagation of longer space scale in near future.

Internal shock models introduced to explain very short time variation of GRBs predicts about a few hundred internal structures or “shells”. Although our resolution can not resolve such fine structure, a simple linear analysis by Aloy et al. [2002] concludes that the time scale of crossing the jet in the progenitor is enough long for the jet to grow the perturbation in the jet.

3.2. Slower Models

On the contrary, the model SA behaves very different. Figure 2 (b) shows rest mass density and Lorentz factor contour of the model SA at t = 10sec. The injected flow from the boundary expands soon. Since the backflow from the head of the jet does not appear, the mass is collected at the head. Figure 3 is for the comparison of pressure jump along the cylindrical axis by the bow shock at the early phase of the simulation. The pressure driven by bow shock in the model SA is smaller than that in the model FC. You can also see some internal shocks in the jet in the model FC. On the contrary the profile in the model SA is very smooth along the axis. The difference is just weather a backflow and reconfinement shock appear or not. The reverse shock separates from the bow shock in time. Then the injected flow is bi-forked. The model SA is the most un-collimated case. As the internal energy in the injected jet increases, the flow collimates well. The model SC is well collimated like the model FC. Because the initial bulk Lorentz factor is small, the maximum Lorentz factor is not so large, only a few. The acceleration occurs at the injection point. We expect that the jet with larger specific internal energy can produce enough large Lorentz factor for GRBs even if the initial flow is non-relativistic one.

4. SUMMARY

We investigate the propagation and dynamics of the jet in the progenitor and ISM of GRBs. The relativistic injected jets (Faster models) can propagate in the progenitor keeping very collimated structure. After the eruption the expansion into ISM occurs. But there still high velocity component along the cylindrical axis within the half opening angle of several degrees. This would be observed as GRBs later. In the collimated outflow, we can see some internal structures caused by the interaction between the jet and backflow.

The model SA which is slower and colder than any other models does not collimate in the progenitor. Smaller velocity can not drive the progenitor gas by a bow shock. The reconfinement shocks which are necessary to keep the collimation does not appear. The central region should form the outflow with directivity with large internal energy.

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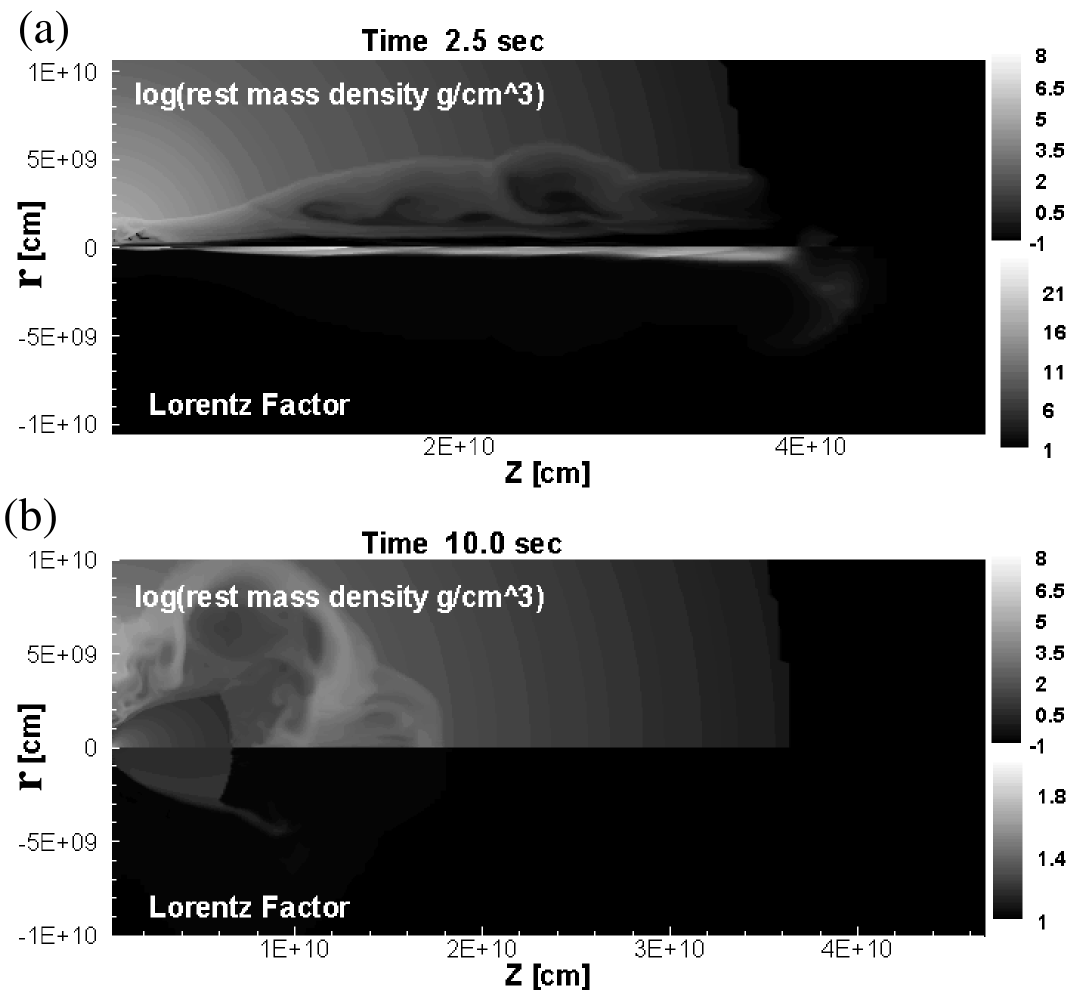

Figure 2: Rest mass density and Lorentz factor contour of the model FC at $t =$ when the break happens.

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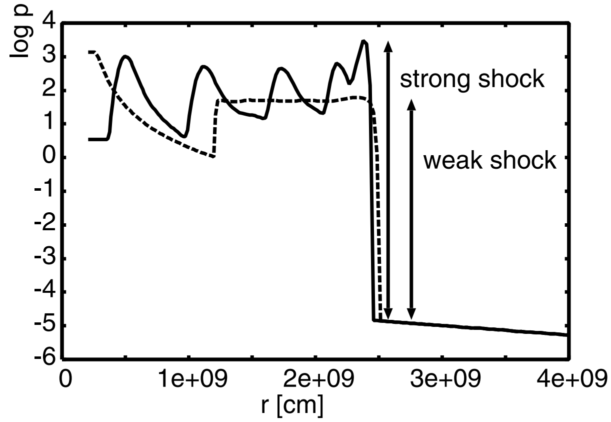

Figure 3: Pressure profile along the cylindrical axis from the inner boundary at the very early phase of the simulations. Two models (SA, FC) are presented for the comparison. The pressure driven by the bow shock in the model FC is higher than that in the model SA. The profile of the model FC has internal structures by the reconfinement shock caused by the interaction between jet and backflow.