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§ Introduction
Some GRBs are Accompanied by Hypernovae

Explosion energy of a hypernova is estimated to be $\sim 1E+52$ ergs, which cannot be explained by the standard scenario of a normal collapse-driven supernova.

Other explosion mechanism is required.
Gravitational Binding Energy is $3 \times 10^{53}$ ergs.

Explosion energy, $1 \times 10^{51}$ ergs, is obtained through weak interactions.
Promising candidates for the energy scales

(a) Gravitational Binding Energy of Accreted Matter onto a central BH. Duration is \( \sim 10 \text{ sec.} \)

MacFadyen and Woosley (1999)

(b) Rotation Energy of a central BH (magnetar). Duration is \( \sim (1-10) \text{ sec?} \)

Blandford-Znajek Process

\[ E_{\text{rot}} \sim \frac{G M_{\text{BH}} M_{\text{acc}}}{V_{\text{H}}} \sim \frac{G M_{\text{BH}} M_{\text{acc}}}{G M_{\text{BH}} C^2} \]
\[ \sim M_{\text{acc}} C^2 = 2 \times 10^{54} \left( \frac{M_{\text{acc}}}{1 M_\odot} \right) [\text{erg}] \]

\[ E_{\text{rot}} = f(a) M_{\text{BH}} C^2 \leq f(a=1) M_{\text{BH}} C^2 \]
\[ = 1.6 \times 10^{54} \left( \frac{M_{\text{BH}}}{3 M_\odot} \right) [\text{erg}] \]

\[ f(a) = 1 - \sqrt{\frac{1}{2} \left[ 1 + \sqrt{1 - a^2} \right]} \]

\[ a = \frac{J C}{G M^2} \leq 1 \]
BH with 3solar mass is put at the center as an initial condition. Rotation is introduced so that the model mimics Heger et al. (00). Thermal energy is deposited at the inner most region, which might be realized when effect of neutrino annihilation is included. Newtonian gravity. Magnetic Fields are not included. Inner most boundary is set to be 50km.
(b) Rotation Energy of a Central BH

Blandford-Znajek Process can be seen in numerical simulations.
§ (a) Gravitational Binding Energy (collapsar model)
Input Physics

- Progenitor: Model E25 in Heger et al. (2000) that is modified so that inner most core has collapsed to form a BH with 1.7Mo.
- 2-D Ideal MHD \((r, \theta)=(150, 30)\) is solved by ZEUS code.
- Initial rotation is same with MacFadyen and Woosley (1999).
- Realistic EOS (Blinnikov et al. 1996).
- Photo-disintegration (N, P, He, O, Ni).
- Newton Gravity (Including self gravity; MBH =1.7Mo).
- Neutrino Cooling (Leakage scheme).
- Neutrino Heating (optically-thin limit).
- Magnetic Field (Vertical + Dipole field: ON· OFF).
Neutrino Processes (1)

Cooling Process  
Electron and positron Capture on free nucleons  
( Epstein and Pethick 1981)  
Pair annihilations  
( Itoh et al. 1999)  
Plasmon decays  
( Itoh et al. 1989)  

Heating Process  
Electron-type neutrino capture on free nucleons  
( Epstein and Pethick 1981)  
Neutrino pair annihilations  
( Goodman et al. 1987)
Neutrino Processes (2)

Example of Heating Processes: Neutrino Pair Annihilation

\[ \dot{Q}(C) = \frac{KG_F^2}{2\pi c} \int \int dx_A^2 dx_B^2 \left( \frac{1 - \cos \psi}{d_A^2 d_B^2} \right)^2 \int \int d\epsilon_{\nu} d\epsilon_{\bar{\nu}} \epsilon_{\nu} \epsilon_{\bar{\nu}} (\epsilon_{\nu} + \epsilon_{\bar{\nu}}) F_{\nu} F_{\bar{\nu}} (1 - f_e^-)(1 - f_e^+) \]

*\( K \) is \((1 - 4 \sin^2 \theta_W + 8 \sin^4 \theta_W)/(6\pi)\) for \(\nu_\mu \nu_{\bar{\mu}}\) and \(\nu_\tau \nu_{\bar{\tau}}\) annihilations

\((1 + 4 \sin^2 \theta_W + 8 \sin^4 \theta_W)/(6\pi)\) for \(\nu_e \nu_{\bar{\nu}}\) annihilation

\(F_{\nu,\bar{\nu}}\) are energy spectrum [cm\(^{-3}\) s\(^{-1}\) GeV\(^{-1}\)] of (anti-)neutrinos

\(f_e^{\pm}\) are fermi bloking factors of electrons/positrons at point C.

Energies of neutrinos are represented by typical ones for each process (Rosswog et al., Itoh et al.).

Heating rates are updated every 100 time Steps (cf. total timestep is \(\sim 1E+6\) steps).
Magnetic Fields

**Initial Condition**

\[
\vec{B}(\vec{r}) = \begin{cases} 
\frac{1}{3} B_0 \left(\frac{r_0}{r}\right)^3 (2 \cos \theta \vec{e}_r + \sin \theta \vec{e}_\theta) & \text{for } r \geq r_0 \\
\frac{2}{3} B_0 (\cos \theta \vec{e}_r - \sin \theta \vec{e}_\theta) & \text{for } r < r_0.
\end{cases}
\]

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 set \( B_0 \) to be 0, 1E+8, 1E+9, 1E+10, 1E+11, and 1E+12 G.

Initial \( |\text{Em/W}| \) are 0, 1.1E-8, 1.1E-6, 1.1E-4, 1.1E-2, and 1.1.

Initial \( |\text{T/W}| \) is 1.3E-2.
§ Results of collapsar model
Simulation with no B-Field

Density contour with velocity fields, Final time is 4.8 sec.

Neutrino cooling Rate [erg/s/cc] at t = 2.2 sec. The rate correlates with Nucleon density.
Neutrino Heating Processes

Energy Deposition Rate [erg/s/cc] By neutrino absorption on free nucleons
At t = 2.2 sec. The rate correlates with Nucleon density.

Energy Deposition Rate [erg/s/cc] By neutrino pair annihilation
at t = 2.2 sec.

Energy is absorbed at the accretion disk

Energy is deposited globally, but With low efficiency
After the shock passage, the released energy was shared by kinetic and thermal energy almost equally ($\sim 1E+52$ erg). Most of thermal energy was lost by neutrino cooling. About 10% was absorbed at the accretion disk ($\sim 1E+51$ erg). Efficiency of neutrino pair annihilation is as low as 0.1% ($\sim 1E+49$ erg).
Simulations with Magnetic Fields

Initial $B=10^9$ G

Density contour
Final time is 2.2sec.

Jet is launched by $B_{\phi}$, which is amplified by winding-up effect.
Can the Jet be a GRB?

Mass, total energy, and terminal bulk lorentz factor of the jet (within 10 degrees, positive total energy, and high velocity (\(=5E+9\) cm/s)) as a function of the initial amplitude of magnetic fields.

<table>
<thead>
<tr>
<th>Initial B</th>
<th>B=1E+10G</th>
<th>B=1E+11 G</th>
<th>B=1E+12G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>2.1E-8Msolar</td>
<td>1.2E-5Msolar</td>
<td>1.5E-4Msolar</td>
</tr>
<tr>
<td>Total Energy (without rest mass)</td>
<td>9.1E+45erg</td>
<td>1.2E+48erg</td>
<td>1.8E+49erg</td>
</tr>
<tr>
<td>Lorentz Factor</td>
<td>1.08</td>
<td>1.05</td>
<td>1.07</td>
</tr>
</tbody>
</table>

These jets can not be GRB jets. 
MJ seems to increase with \(B_0\), since the jet is launched earlier for larger \(B_0\). 
Simulation for longer physical time is required?
At least, special relativistic MHD is required.
§ (b) Rotation Energy of a Central BH (BZ-Process Model)
Formulation of General Relativistic Magneto-Hydrodynamic Code (GRMHD Code)
Gammie, McKinney, Toth 03

**Basic Equations**

\[ \frac{1}{\sqrt{-g}} \partial_{\mu} (\sqrt{-g} \rho u^\mu) = 0 \]

\[ \partial_i (\sqrt{-g} T^i_v) = -\partial_i (\sqrt{-g} T^i_v) + \sqrt{-g} T^j_b \Gamma^b_{\nu k} \]

**Additional Equations**

\[ \frac{1}{\sqrt{-g}} \partial_t (\sqrt{-g} B^i) = 0 \]

**Conserved Variables**

\[ p = (\gamma - 1)u \]

**Solver**

\[ \partial_t U(P) = -\partial_i F^i(P) + S(P) \]

**Conserved Variables**

\[ U \equiv \sqrt{-g} (\rho u^i, T^i_t, T^i_i, B^i) \]

**Newton-Raphson Method**

**Primitive Variables**

\[ P = (\rho, u, v^i, B^i) \]

**Flux term (HLL Method)**

\[ F = \frac{c_{\min} F_R + c_{\max} F_L - c_{\max} c_{\min} (U_R - U_L)}{c_{\max} + c_{\min}} \]

\[ c_{\max} \equiv \max(0, c_{+,R}, c_{+,L}) \]

\[ c_{\min} \equiv -\min(0, c_{-,R}, c_{-,L}) \]

**Slope (2nd order in Space, 3rd in time)**

Mimmod or Monotonized Center

TVD Runge-Kutta
§ Results of GRMHD Simulation
Fishbone and Moncrief’s Problem

\( u_r u_r \) constant \( a=0.938 \), no-magnetic field \( N \times N=150 \times 150 \)

\( T=0 \)  \( T=1200 \)

c.f. e.g. McKinney and Gammie 2004, McKinney 2006

\( G=c=M=1 \)
Fishbone and Moncrief’s Problem
(cont’d)

$A_\phi \propto \max(\rho/\rho_{\text{max}} - 0.2, 0)$

$a = 0.938$, with-magnetic field $N \times N = 150 \times 150$

$\beta_{\text{min}} = 100$

$R < 60$

c.f. e.g. McKinney and Gammie 2004, McKinney 2006

$R < 300$

$T = 1200$

$G = c = M = 1$
§ Discussion
Effects of Neutrino Pair Annihilation with General Relativity

c.f. e.g. Popham et al. (1999)

Effective Potential

Geodesic of Neutrinos

Disk structure is also changed.
Properties of the Central Engine will be constrained by simulations of propagation of the Jet.


\( \Gamma_0 = 1.15 \)
\( \varepsilon_0/c^2=0.1 \)
Mildly Relativistic Jet
Related with X-ray flash?

\( \Gamma_0 = 5 \)
\( \varepsilon_0/c^2=30 \)
Highly relativistic
Jet. Related with GRB?
§ Brief Comments on Explosive Nucleosynthesis in a GRB (Hypernova)
Results of Explosive Nucleosynthesis including effects of Bi-polar explosion applied for SN1987A

Mass Fraction of $^{56}\text{Ni}$

Spherical Explosion

Jet like Explosion

S.N. et al. 97, S.N. 00

Model S1: Spherical Model
Model A1: $V_p/V_e = 2:1$
Model A2: $V_p/V_e = 4:1$
Model A3: $V_p/V_e = 8:1$

2D Simulation, 6Msolar He Core
Explosion energy is fixed to be $1\times10^{51}$ erg
Nuclear Reaction Network contains 250 nuclei
Explosion Energy is injected at the inner boundary with asymmetric injection rate so that jet like explosion occurs.
One of Our Predictions on GRBs in 2000.

Velocity Distribution of Iron

We comment on the jet-induced explosion of a collapsing star (MacFadyen & Woosley 1998; Khokhlov et al. 1999). It is a very attractive theory because it has a possibility to explain a lot of observational facts and to be an origin of the γ-ray bursts (MacFadyen & Woosley 1998; Khokhlov et al. 1999). When we believe the correlation between a γ-ray burst and a super(hyper)nova (Kulkarni et al. 1998; Galama et al. 1998), such a jet-induced explosion model will be a convincing one for the γ-ray burst model. In this case, we note, a bipolar profile of iron like the one seen in Figure 13 should be observed when a γ-ray burst occurs near us, that is, in our galaxy and the Magellanic clouds. Such an obser-


c.f. Maeda et al. 2002, 2005
Observations of Line Profiles of Hypernovae

Mazzali et al. 05

Oxygen Line
Where is $^{56}$Ni synthesized?

Duration of Explosion is set to be 10 sec.

All explosion energy is Deposited Initially.

**Abundance is small.** Faint HN will Be possible.

Origin of $^{56}$Ni in a hynernova is not unknown. Another possibility: Ejection from the accretion flow. (e.g. MacFadyen and Woosley 99)

Amount of $^{56}$Ni synthesized in the jet depends on the duration of the jet, if $^{56}$Ni is synthesized in the Jet.
Faint Hypernova?

GRB060614
Gehrels et al. Nature 2006
c.f. Tominaga et al. 2007

GRB060505

The small amount of nickel ($< 10^{-3} M_\odot$)

Is preferred.

Della Valle et al. 2006

Duration?

Small ejection
From the accretion Disk?

Short GRB?
§Particle Acceleration and High Energy Phenomena in GRBs
Where are very high-energy neutrinos produced?

$10^{13} - 10^{15}$ cm

Figure by Piran 2003

- Inner engine
- Ultra-relativistic jet
- Internal shocks

Dermer 02  TeV-PeV Neutrinos

GeV Neutrinos

- Bahcall and Meszaros 00
- Waxman and Bahcall 97

- TeV-PeV Neutrinos
  - Murase and S.N. 06
  - Waxman and Bahcall 01

- TeV-PeV Neutrinos
Particle in Cell Simulation

Formation of a Collision-less shock with magnetic Fields In the Up-stream

Kato and S.N. 2007 in prep
High energy neutrino emission from Gamma-Ray Burst

K. Murase and S. N. PRD, 7 3 , 0 6 3 0 0 2 ( 2 0 0 6 )

High energy neutrino background is estimated by using GEANT4.

GRB rate was assumed to be proportional to SFR.

Much neutrinos are produced when photo-pion production is so effective that internal shocks are optically thick against ultra high energy protons.

UHECRs may also be explained if internal shocks are optically thin against ultra high energy protons.

Due to the effect of multi-pion production, our model predicts higher flux of neutrinos at high energy region.

GRB neutrinos should be correlated with GRBs. Thus they can be distinguished from other type of high energy neutrinos.
§ Summary
Summary on the central engine of Long GRBs

Neutrino heating processes have been included in the collapsar model.

It is found that neutrino heating processes are insufficient to launch a jet in this study.

A Jet is launched by magnetic fields, although this jet is non-relativistic at present.

Simulations of the order of 10sec may be required to generate a powerful jet by special (general) relativistic MHD code.

Effects of general relativity should be important for the formation of relativistic jet (BZ-process, Neutrino Heating), which we are planning to study using our GRMHD code with microphysics.
Numerical simulation of Blandford-Znajek Process

$T=60, \ c=G=M=1$


\[ \dot{E} = 2\pi \int_{0}^{\pi} d\theta \sqrt{-g(\pi - T^r r)} = \frac{C^2\pi}{32} a^2 \int_{0}^{\pi} d\theta \sin^3 \theta \]

\[ *F^{tr} = C/(r^2 + a^2 \cos^2 \theta) = C\sin \theta/\sqrt{-g} \text{ in KS} \]

Monopole solution

For $a \ll 1$

Blandford and Znajek (1997)
1-D Shock Tube Problems

density $\rho$ vx vy

$v_z$ By Bz gamma

<table>
<thead>
<tr>
<th></th>
<th>$\rho$</th>
<th>$p$</th>
<th>$v^x$</th>
<th>$v^y$</th>
<th>$v^z$</th>
<th>$B^x$</th>
<th>$B^y$</th>
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<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
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<tr>
<td>right state</td>
<td>0.1</td>
<td>1.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
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</table>

<table>
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<th>$B^x$</th>
<th>$B^y$</th>
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<td>10.0</td>
<td>-7.0</td>
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2-D Shock Tube problem

<table>
<thead>
<tr>
<th>y</th>
<th>x</th>
<th>region A</th>
<th>region B</th>
<th>region C</th>
<th>region D</th>
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<tr>
<td>0</td>
<td>1</td>
<td>region A</td>
<td>region B</td>
<td>region C</td>
<td>region D</td>
</tr>
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</table>

$N \times N = 400 \times 400$
Cylindrical explosion problem

density

pressure

gamma

Div B
Gammie’s Inflow Problem

\[ a = 0.5, \, T = 1 \text{(GM/c}^3) \]

- **BL-Coordinate**
- **KS-Coordinate**

<table>
<thead>
<tr>
<th>( \rho )</th>
<th>( u^r )</th>
<th>( U^\phi )</th>
<th>( U_\phi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^2 )</td>
<td>( B^\phi )</td>
<td>( V^r )</td>
<td>( V^\phi )</td>
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