Collapsar and Magnetar Models for Long-Duration Gamma-Ray Bursts

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§ Introduction
History of the Numerical Study on the Central Engine of Long-GRBs.

• First report on the association of a GRB with a hypernova was done in 1998.

  Outline of Explosion Mechanism is still under debate. BH (Collapsar) or NS (Magnetar)? Neutrino or B-Field?

• Rotating Black Hole with Neutrino Heating?
• Rotating Black Hole with Strong B-Fields?
• Rotating Magnetars?
Black Hole with Neutrino Heating

MacFadyen and Woosley 99 Newtonian Without Neutrino physics

S.N. +07 Newtonian With some Neutrino physics.
Black Hole with Strong B-Fields

Barkov and Komissarov 08
2D-GRMHD, $a=0.9$
With Some Microphysics
$\Gamma < \text{a few. Density Contour}$.

S.N. 09
2D-GRMHD, $a=0.5$
Without Microphysics.
$\Gamma < \text{a few. Plasma beta}$.
3D-GRMHD Simulation

S.N. 2012, in prep.

~3000km
Black Hole Formation

Contours of entropy per baryon

Full 2D-GRHD with Microphysics

Sekiguchi and Shibata 11

Full 3D-GRHD without Microphysics

Ott+11
Magnetar Scenario

Komissarov and Barkov 07
2D-GRMHD with some Microphysics
\( \frac{v^r}{c} \approx 0.5. \)

Bucciantini+09
2D-SRMHD without Microphysics
Lorentz factor = 5-10
Magnetar Formation

Takiwaki et al. 09
SRMHD, Neutrino Physics, Realistic EOS. Upto 100ms. $\Gamma< \text{a few}$.
See also Takiwaki, Kotake, S.N., Sato 04.

Burrows et al. 07
Newtonian-MHD, Neutrino Physics&EOS. Upto 0.5-0.6sec.
Study on a Rotating Black Hole with Strong B-Fields by a General Relativistic Magneto-Hydrodynamic (GRMHD) code

2D/3D GRMHD Codes with MPI.  
2D/3D SRMHD with AMR & MPI.  
S.N. 2012, in prep.

Yukawa institute’s MAGNETO-hydro (YAMATO) code  
YAMATO (大和) =Old Name of Japan

GRMHD Code is necessary to see Blandford-Znajek Process.
Blandford-Znajek Process can be seen Numerically Now

This solution can be used to check the validity of numerical codes. Numerical Simulation is necessary for large $a$ and different $B$-fields.

\[ \dot{E} = \frac{C^2 \pi}{24} \frac{a^2}{M^2} + \frac{\pi C^2}{1080} \frac{a^4}{M^4} (56 - 3\pi^2) \]

$C$: Amplitude of B-Field. $a$: Kerr-Parameter.

(Split-) Monopole Solution.
Initial Condition for GRB Simulations

• Fastly Rotating Massive Stellar Model (12TJ) by Woosley and Heger 2006.
• Fe core (1.82M\text{sol}) is extracted and a rotating black hole is put instead.
• $M_{\text{BH}}=2\text{M\text{sol}}, \, a=0.5$ (Fixed Kerr Metric).
• $\Gamma=4/3$
• $A_\phi \propto \max(\rho/\rho_{\text{max}} - 0.2, 0) \sin^4 \theta$
• Minimum value of $p_{\text{gas}}/p_{\text{mag}} = 10^2$
Simulation of a Collapsar

Density contour in logarithmic scale (g/cc)

Dynamics is followed up to 1.77sec from the collapse.
Dependence of Dynamics on Rotating Black Hole Density Structure at $T=1.6\text{sec.}$

- $a=0$
- $a=0.5$
- $a=0.9$
- $a=0.95$

Density Structure at $T=1.6\text{sec.}$

$\sim 15000\text{km}$
Blandford-Znajek Flux and Jet Energy

BZ (outgoing poynting)-Flux
In unit of $10^{50}$ erg/s/Sr at $T=1.5760$ sec.
Kerr Parameter, $a=0.95$.

Jet Energy at $t=1.5750$ sec for $a=0, 0.5, 0.9, 0.95$ (Solid Curves).

Faster is Better

$\theta = 10^\circ$
$\theta = 5^\circ$

$\sim 12$ km
3D-GRMHD Simulation of GRBs

S.N. 2012, in prep.

256×256×32

a=0.9

~3000km
Same Simulations.
Left: 3D Image.
Density+B-fields.

Bottom: 2D Slice
Density+Poloidal B-Fields

~150km

a = 0.9
T ~ 0.85 sec
S.N. 2012, in prep.

\( a = 0.9 \)
\( T \approx 0.9 \text{sec.} \)

Same Simulations.
Left: 3D Image.
Density+B-fields.

Bottom: 2D Slice
Density+Poloidal B-Fields

\( \sim 150 \text{km} \)
T ~ 0.35 sec.
T ~ 0.8 sec.
T ~ 0.85 sec.
T ~ 0.9 sec.

~150 km
For Fine Resolution Simulations: SRMHD Code with Adaptive Mesh Refinement (AMR)

S.N. 2012, in prep.

Paramesh:
K(京: 10Peta-Flops) Computer is Coming Soon (2012-).

548,352 Cores
Memory 8GB per 1 Core
100GB/s.
Summary on the Central Engine of LGRBs

• Outline of Explosion Mechanism of LGRBs is still under debate. Lots of things to do.

• Rotation Energy of a Black Hole can be extracted with a help of Magnetic Fields (Blandford-Znajek Effect).

• Faster is better: Rapidly rotating Black Hole can drive an energetic GRB jet.

• GRB simulations by 3D GRMHD code are being done. AMR will be attached. 10-Peta Flops Computer will be open very soon.
Slide Show of Our Studies
Gamma-Ray Bursts as a Treasure Box of Physics & Mysteries

Nucleosynthesis
Central Engine

Photospheric
Emission?

UHECRs?
Neutrinos?

GRB/SN
Remnants?

GRB Cosmology?

Figure from P. Meszaros
Explosive Nucleosynthesis in Jet-Like SNe/GRBs by FLASH. S.N.+ 03, 06. Ono, S.N.+ 2012, in prep.
Simulations for the Photospheric Model

Mizuta, S.N., Aoi 2010

(Also, F.Ryde’s talk and D.Lazzati’s talk)
Spectrum, E_peak, and L_peak

- Superposition of BB spectrum makes the spectrum at low-energy side a little bit softer, although it is not enough to explain alpha.
- Yonetoku (and Amati) Relation is almost reproduced except for some systematic difference.
Monte-Carlo Simulations for the Band-Function

Observation

Band-Function can be reproduced by structured photospheric model.

Numerical Set-Up & Monte-Carlo Calculations

Ito, S.N. et al. 2012, in prep

Calculation

\[ E^2 N_E \text{ (erg cm}^{-2} \text{s}^{-1}) \]

Photon Energy (MeV)

\[ 10^{53} \text{erg/s} \quad r_0 = 10^8 \text{cm} \quad n = 5 \times 10^6 \]

\[ \Gamma_0 = 400 \quad \Gamma_1 = 200 \quad \tau = 23 \]

\[ \Gamma_0 = 200 \quad \Gamma_1 = 100 \quad \tau = 367 \]

\[ \theta_j = 1 \quad \theta_0 = 0.5 \]

\[ \alpha = 0 \]

\[ \alpha = -1 \]

\[ \beta = -2.5 \]

\[ \beta = 3 \]
First Results of Telescope Array are Open Now

BR/LR stereo
(~22g/cm² acc.)

Green:
35 events
E > 40 EeV

Black: LSS model (smearing angle = 6°)

T@Utah preliminary
Re-analysis of 215 GRBs’ Neutrinos

He, Liu, Wang, S.N.+ 12

Expected Neutrino Flux from 215 GRBs.

See also Li 12, Hummer +12
Murase and S.N. 06a, 06b

\( \alpha = 1, \beta = 2, \) fluence \( F_{\gamma}^{ob} = 10^{-5} \text{erg cm}^{-2} \) (in 10ke\text{V} to 1MeV), \( z = 2.15, \epsilon_{\gamma,b}^{ob} = 200\text{keV}. \)

\( L_\gamma = 10^{52} \text{erg s}^{-1}, \) bulk Lorentz factor \( \Gamma = 10^{2.5}, \) the observed variability timescale \( t_{\gamma}^{ob} = 0.01\text{s} \) and the baryon ratio \( \eta_p = 10. \)
Study on Supernova Remnant RXJ1713.7-3946 with CR-Hydro-NEI Code

Lee, Ellison, S.N. 2012
Ellison+ 2010 and References there in.

RXJ1713 in TeV-Gamma (Color, HESS)
And X-rays (Contour, ASCA)
Age is about 1600yrs.
Supernovae and Gamma-Ray Bursts in Kyoto, 2013

• Oct.-Nov. in 2013.
• 2 weeks for Conferences (SN and GRB)
• 3 weeks for Workshops (Seminars & Discussions).

Photo from GRB2010, Kyoto In April.
You can Stay More in Kyoto.

- Program for Ph.D Students or Postdocs
  Period: 1-3 Months.
  Flight fee & accommodation fee are covered, at least.

- Some Programs for Visiting Staffs.

- Some Postdoc Positions will be open
  (YITP, Kyoto Univ. and JSPS).
Kyoto in Spring
Kyoto in Summer
Kyoto in Autumn
Kyoto in Winter
Outline of Explosion Mechanism of LGRBs is still under debate.
Rotation Energy of a Black Hole can be extracted with a help of Magnetic Fields (Blandford-Znajek Effect).
Faster is better: Rapidly rotating Black Hole can drive an energetic GRB jet.
GRB simulations by 3D GRMHD code are being done. AMR will be attached. 10-Peta Flops Computer will be open very soon.
Explosive Nucleosynthesis is being studied by Flash code.
Photospheric Models are studied by numerical simulations and Monte-Carlo calculations.
UHECRs, VHE-Neutrinos, SNRs are being studied.
5 Week Conferences and Workshops on SNe and GRBs will be held in Kyoto, 2013, Oct.-Nov.
Programs for Visitors and Postdocs.
Stagnation Region

Kerr Parameter, $a=0.95$
$T=160000$ (=1.5760 sec).
Stagnation Region can be seen At $R=15$ (=45km) in the Jet.

Density Contours in logarithmic scale (g/cc) with Velocity Fields
Time evolution of the Photo-sphere and Thermal Emission

Left: Evolution of the temperature at the photo-sphere viewed from the jet axis.

Right: Beaming factor at the photo-sphere.

Superposition of thermal emissions from each area of the photosphere is observed.
Re-analysis of 215 GRBs’ Neutrinos

He, Liu, Wang, S.N.+ 12

Expected Neutrino Flux from a single GRB

\( \alpha = 1, \beta = 2 \), fluence \( F_{\gamma}^{\text{obs}} = 10^{-5}\,\text{erg cm}^{-2} \) (in 10keV to 1MeV), \( z = 2.15 \), \( \epsilon_{\gamma,b}^{\text{obs}} = 200\,\text{keV} \)

\( L_\gamma = 10^{52}\,\text{erg s}^{-1} \), bulk Lorentz factor \( \Gamma = 10^{2.5} \), the observed variability timescale \( t_{\nu}^{\text{obs}} = 0.01\,\text{s} \) and the baryon ratio \( \eta_p = 10 \).

Expected Neutrino Flux from 215 GRBs.
IC40/59 can draw a constraint on GRB-Neutrino scenarios with a help of some Empirical Relations

He, Liu, Wang, S.N.+ 12.

215 GRBs’ Neutrinos

Gray: All GRBs are assumed to be same (IceCube Collaboration).

Green: Numerical Model with Lv relation (2011)

Red: Same with ICC, but for Numerical Model.

Blue: Numerical Model with Ghirlanda relation (2011)

\[ \Gamma_L = 118 E_{\text{iso,52}}^{0.26} \]

\[ L_{\gamma,G,52} = 7.54 \left[ \epsilon_{\gamma_b,\text{MeV}}^0 (1 + z) \right]^{1.75} \]

\[ \Gamma_G = 29.8 E_{\text{iso,52}}^{0.51} \]

\[ L_{\gamma,G,52} = 7.54 \left[ \epsilon_{\gamma_b,\text{MeV}}^0 (1 + z) \right]^{1.75} \]
Gamma-Rays look Leptonic Origin for RXJ1713.7-3946

Lee, Ellison, S.N. 2012

Ellison+ 2010