Gamma ray Bursts powered by turbulence and reconnection

Huirong Yan

Kavli Institute of Astronomy & Astrophysics, Peking U

References:
Lazarian, Petrosian, Yan & Cho, 2003;
Zhang & Yan 2011
GRBs: brightest electromagnetic event in the universe!

A typical burst releases as much energy in a few seconds as the Sun will in its entire 10-billion-year lifetime. Extragalactic origin with record redshift up to $z \sim 8$. 

2704 BATSE Gamma-Ray Bursts
Standard Fireball Shock Model

GRB prompt emission: from internal shocks and photosphere
Afterglow: from external shocks
Internal shock (IS) model

Collisions between mini shells launched from central engine create relativistic shocks.
**INTERNAL SHOCK (IS) MODEL**

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- Central engine driven variability
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- ✓ Central engine driven variability

- ✗ Efficiency problem: need large $\Gamma$ ratio between shells
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✗ efficiency Problem: need large $\Gamma$ ratio between shells

✗ fast cooling: $N(E) \propto E^{-3/2}$ inconsistent with observed spectral index of -1

✗ Electron number excess problem
**Internal Shock (IS) Model**

- Collisions between mini shells launched from central engine create relativistic shocks
- Central engine driven variability
- Efficiency problem: need large $\Gamma$ ratio between shells
- Fast cooling: $\propto E^{-3/2}$ inconsistent with observed spectral index of -1
- Electron number excess problem
- Missing photosphere: thermal emission is missing
Expected photosphere emission from a fireball

Sigma: ratio between Poynting flux and baryonic flux:

\[ \sigma \equiv \frac{F_P}{F_b}; \text{ at least } \approx 20, 15 \text{ for GRB 080916C} \]

Confirmed by Fan (2010) with a wider parameter space study.
Is the band function emission from the photosphere?

- Superposition from many shells (Toma et al. 2010; Li 2009)?
  - Contrived fine-tuning
  - Seems not supported by data with finer temporal resolution

Abdo et al. (2009)
Grbs powered by reconnection

Highly magnetized GRBs have been suggested by observations. Magnetic energy is the natural reservoir of energy.

In the presence of turbulence, reconnection is expedited depending on the level of turbulence.
Fast Reconnection in turbulence

cf. talk by Lazarian

\( V_r, u_p = V_{A\text{min}} \left[ \left( \frac{L}{L_x} \right)^{1/2}, \left( \frac{L}{L_x} \right)^{1/2} \right] M_A^2 \)

- \( l \) - turbulence injection scale
- \( M_A \) - Alfven Mach number

(Lazarian & Vishniac 1999)
Reconnection rate can be both slow and fast, naturally explains the episodic feature observed in GRBs.

Fast bursty reconnection eventually occurs as a nonlinear feedback of the increased stochasticity of the B field lines.

The reconnection events start from limited volumes and then spread in the form of a chain reaction as the energy is fed back to the turbulence and induces dramatic change in the magnetic field topology.
A New Model in the High-σ Regime:
The ICMART Model

(Internal Collision-induced MAgnetic Reconnection & Turbulence, Zhang & Yan 2011)

Basic Assumptions:

• The central engine launches a high-σ flow. The σ is still \( \sim (10-100) \) at \( R \sim 10^{15} \) cm.
• The central engine is intermittent, launching an outflow with variable Lorentz factors (less variable in σ).
Astrophysical systems are not perfectly symmetric systems. For example, current-driven kink instability may develop in the jet (e.g., Mizuno et al. 2009a), which would introduce a slight misalignment of the magnetic field axes in two consecutive “shells.” This would result in a small cross section near the magnetic axes that have opposite orientations in the two shells.
Fast reconnection triggers a GRB at large $R$
Turbulent Reconnection is needed to power GRBs

In order to reach GRB luminosity, the effective global reconnection rate has to be close to $c$

\[
\Gamma^2 \frac{B'^2}{8\pi} 4\pi R^2 \frac{\Delta'}{\Delta t'} \sim L_\gamma
\]

\[
V'_{\text{rec,global}} = \frac{\Delta'}{\Delta t'} \sim \frac{L_\gamma}{L_w} \frac{1+\sigma}{\sigma} c \sim c
\]

Relativistic Sweet-Parker reconnection speed is $<< c$ (Lyubarsky 2005).

\[
V'_{\text{rec,local}} = V_A s^{-1/2} << c
\]

\[
s \equiv \frac{\lambda V_A}{\eta} >> 1
\]

Turbulent reconnection (Lazarian & Vishniac 1999) can become comparable to Alfven speed and close to $c$ with sufficient turbulence developed in the relativistic regime (cf. Cho’s talk).
Comparison of the models

<table>
<thead>
<tr>
<th>Feature</th>
<th>IS model</th>
<th>ICMART</th>
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<tbody>
<tr>
<td>Variability from central engine</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>High efficiency</td>
<td>✗</td>
<td>✔️</td>
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<tr>
<td>Fast cooling problem</td>
<td>✗</td>
<td>✔️</td>
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<tr>
<td>Electron Excess problem</td>
<td>✗</td>
<td>✔️</td>
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<td>Missing photosphere</td>
<td>✗</td>
<td>✔️</td>
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</table>
Difference from other models

The EM model proposed by Lyutikov & Blandford (2003) invokes an extremely high-σ (σ > 10⁶) at the deceleration radius.

The variability in this model has no direct connection with the central engine activity, while the evidence of an engine-related variability (e.g., those in X-ray flares) is mounting.

Models in the MHD regime (Thompson 1994; Spruit et al. 2001; Drenkhahn & Spruit 2002; Vlahakis & Konigl 2003; Giannios 2008; Komissarov et al. 2009). These models invoke magnetic dissipation at smaller radii to enhance the photosphere emission. At large radii, the outflow is no longer PFD, so that the IS model can still operate.

The main difference between the ICMART model and other MHD models is whether the magnetic energy is released abruptly at a large radius or continuously at small radii.
Variabilities are naturally explained.
Open question: Acceleration vs. Heating

- Kinetic energy vs. ohmic heating
- 1st order vs. 2nd order acceleration
- Bulk heating vs acceleration of MW tail particles

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de Gouveia Dalpino & Lazarian (2005)

Magnetic "clouds"

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Lazarian (2005)
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Bulk heating vs acceleration of MW tail particles
- Nonthermal damping is found less than 10% of thermal damping during the transit time acceleration by fast modes (Petrosian, Yan & Lazarian 2006).

References:
- de Gouveia Dalpino & Lazarian (2005)
- Lazarian (2005)
TURBULENCE ACCELERATION MODEL

Turbulence is naturally generated during shell shell collisions and reconnection process.

Turbulence energy is cascaded down to small scales through weakly coupled fast modes and Alfven modes.

Energy in both channels can be transferred to particles.

The acceleration efficiency is much enhanced in relativistic turbulence since the electric fluctuations are \( \delta E \sim \beta_A \delta B \) larger than the magnetic ones.
Alfven modes

$\mathbf{B}$

$\mathbf{l}_\perp << \mathbf{l}_\parallel r_L$

Resonant Interaction is substantially reduced! (Yan & Lazarian 02, 04, 08)

Alfven turbulence

Whistler turbulence

electrons
Channel 2: through both fast modes cascade!

TTD Acceleration by fast modes is an important mechanism to generate energetic electrons (Lazarian et al. 2003, Yan, Lazarian & Petrosian 2008).
Summary

- Traditional fireball model faces big problems.
- Recent understandings of MHD turbulence and reconnection shed lights on GRB physics.
- Highly magnetized GRBs are dominated by nonthermal emission released during the fast reconnection events.
- The central engine is intermittent, launching an unsteady wind. The shells interact via collisions, which distort the field lines, making the field more and more turbulent.
- At a certain large radius, turbulence is sufficient to trigger a fast reconnection, corresponding to a GRB pulse.
- Further modeling of both acceleration by reconnection and turbulence is necessary to make quantitative predictions on issues like acceleration vs. heating.