How did Fermi revolutionize our physical understanding of GRB prompt emission?

Bing Zhang

University of Nevada Las Vegas

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(Celebrating 10 Years of Fermi)
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Fermi revolution: Most beautiful figure in astrophysics: GW170817/GRB 170817A
Today’s topic:
The Physics of Gamma-Ray Bursts
Prompt GRB Emission: a Mystery

*What* is the jet composition (baryonic vs. Poynting flux)?

*Where* is (are) the dissipation radius (radii)?

*How* is the radiation generated (synchrotron, Compton scattering, thermal)?
Early GRB model:
The fireball shock model
(Paczynski, Meszaros, Rees, Piran, Daigne/Mochkovitch ...)

central photosphere internal external shocks
engine (reverse) (forward)
Before Fermi: Fireball Predictions: Internal shock synchrotron vs. photosphere

Meszaros & Rees (00)

Daigne & Mochkovitch (02)

Pe’er et al. (06)
Fermi Revolution:
Much wider spectral window

Launched on June 11th, 2008
Fermi surprise #1: GRB 080916C
(Abdo et al. 2009, Science)
Fermi Surprise #1: Photosphere component missing

Sigma: ratio between Poynting flux and baryonic flux:

\[ \sigma = \frac{L_P}{L_b} \] at least \( \sim 20, 15 \) for GRB 080916C

Zhang & Pe’er (2009)

Cf. Guiriec et al. (2015)
The simplest fireball model does not work!

Theorists’ view cannot be more diverse since the establishment of cosmological origin of GRBs!

Three distinct views:

The observed component is:
- The internal shock component
- The photosphere component
- Neither (Poynting flux dissipation component)
Modified Fireball Model (1)

**central engine**  **photosphere**  **internal shocks**  **external shocks**
(reverse)  (forward)

*GRB prompt emission is from internal shocks*
*Photosphere emission suppressed*
Modified Fireball Model (2)

central engine  photosphere  internal shocks  external shocks
(reverse)  (forward)

GRB prompt emission: from photosphere
Internal shock emission suppressed
The ICMART Model

(Internal Collision-induced MAgnetic Reconnection & Turbulence)

Zhang & Yan (2011)

Earlier work: Lyutikov & Blandford; Narayan & Kumar …
GRB central engine parameters \((\eta, \sigma_0)\)

- Energy per baryon \(>> 1\)
- Energy in three forms
  - Thermal: \(\eta, \Theta\)
  - Magnetic: \(\sigma\)
  - Kinetic: \(\Gamma\)

\[
\mu_0 = \frac{E_{\text{tot},0}}{M c^2} = \frac{E_{\text{th},0} + E_{\text{P},0}}{M c^2} = \eta(1 + \sigma_0).
\]

Neglect radiation, one has

\[
\mu_0 = \eta(1 + \sigma_0) = \Gamma \Theta (1 + \sigma).
\]

\[
\Gamma_{\text{max}} = \mu_0 \approx \begin{cases} 
\eta, & \sigma_0 \ll 1; \\
\sigma_0, & \eta \sim 1, \sigma_0 \gg 1.
\end{cases}
\]
Energy Flow in GRBs

- Gravitational
- Spin (kinetic)
- Thermal
- Poynting flux
- Kinetic
- Radiation

- Thermal acceleration
- Magnetic acceleration
- Magnetic dissipation
- Photosphere emission
- Shock dissipation
Basic Theoretical Framework

Fig. 7.5 An energy flow chart for GRBs.

- Gravitational
- Spin (kinetic)
- Thermal
- Poynting flux
- Kinetic
- Radiation

Energy Flow in GRBs

Fireball model
Basic Theoretical Framework

Figure 7.5: An energy flow chart for GRBs.

- Early on, a reverse shock propagates into the jet itself and crosses the jet in a short duration of time. If the central engine is long-lived or if the ejecta has a Lorentz factor "stratification" (a wide distribution of $\Gamma$), the reverse shock can be long-lived. Emission from these external shocks powers the long-lasting afterglow emission of GRBs.

- The spatial range between the photosphere (included) and the external forward/reverse shocks (excluded) is called an internal emission site of a GRB. GRB prompt emission likely originates from one or more internal emission regions. The radiation mechanism of prompt emission is an open question. The leading candidates include synchrotron radiation from an optically thin region, and quasi-thermal, Comptonized emission near the photosphere. Synchrotron self-Compton (SSC), external inverse Compton (EIC), and hadronic cascade have been also discussed in the literature to account for (part of) the prompt emission spectra.

- The main radiation mechanism of afterglow emission has been identified as synchrotron radiation from the external shocks.

Figure 7.4 is a cartoon picture of the evolution of a GRB jet within this general theoretical framework. Figure 7.5 outlines the energy flow in a GRB jet, describing how various forms of energy convert from one to another and give rise to the observed radiation from GRBs.
An energy flow chart for GRBs.

Medium, as a relativistic shock propagates into the medium. Early on a reverse shock propagates into the jet itself and crosses the jet in a short duration of time. If the central engine is long-lived or if the ejecta has a Lorentz factor “stratification” (a wide distribution of $\Gamma$), the reverse shock can be long lived. Emission from these external shocks powers the long-lasting afterglow emission of GRBs.

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Initially magnetized internal shock model
Fig. 7.5 An energy flow chart for GRBs.

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- If the central engine is long-lived or if the ejecta has a Lorentz factor "stratification" (a wide distribution of $\Gamma$), the reverse shock can be long-lived.
- Emission from these external shocks powers the long-lasting afterglow emission of GRBs.

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- GRB prompt emission likely originates from one or more internal emission regions.
- The radiation mechanism of prompt emission is an open question. The leading candidates include synchrotron radiation from an optically thin region, and a quasi-thermal, Comptonized emission near the photosphere. Synchrotron self-Compton (SSC), external inverse Compton (EIC), and hadronic cascade have been also discussed in the literature to account for (part of) the prompt emission spectra.

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**ICMART**

*Internal collision-induced magnetic reconnection & turbulence (ICMART) model*
Fermi Surprise #2: GRB 090902B

(Abdo et al. 2009; Ryde et al. 2010; Zhang et al. 2011; Pe’er et al. 2012)

A clear photosphere emission component identified

Fireballs do exist!
But are special & rare!

A new high-energy component extending to high energies
More cases:
Three elemental components?

* Ackerman et al. 2010, 2011
* Zhang et al. 2011
* Guiriec et al. 2011; Axelsson et al. 2012
* Guiriec et al. 2015
The “Band” function spectrum

\[ N(E) = \begin{cases} 
A \left( \frac{E}{100 \text{ keV}} \right)^\alpha \exp \left( -\frac{E}{E_0} \right), & E < (\alpha - \beta)E_0, \\
A \left[ \frac{(\alpha-\beta)E_0}{100 \text{ keV}} \right]^{\alpha-\beta} \exp(\beta - \alpha) \left( \frac{E}{100 \text{ keV}} \right)^\beta, & E \geq (\alpha - \beta)E_0 
\end{cases} \]

Josh Grindley (The 2009 Fermi Symposium, Nov. 2-5, at the David Band special session):
Challenge to theorists: Find the physical meaning of “Band” function in 10 years!
Debate: What is the origin of the “Band” component?

Two distinct views:

- The Band component is the synchrotron emission in optically-thin region.
- The Band component is reprocessed quasi-thermal emission in a dissipative photosphere.

Nava et al. (2011)
Synchrotron Model: Fast Cooling Spectrum Can Be Harder!
(Uhm & Zhang, 2014, Nature Physics, 10, 351)

- B is decreasing with radius
- Electrons are not in steady state
- Electron spectrum deviates significantly from -2 below the injection energy
Synchrotron Model: close to (but wider than) the “Band” Function
(Uhm & Zhang, 2014, Nature Physics, 10, 351)

- In the BATSE or GBM band, the spectrum mimics a “Band” function with “correct” indices: $\alpha \sim -1$, $\beta \sim -2.2$

Requirement: Large emission radius where B is low!
“Band” Function is made from synchrotron
(B.-B. Zhang et al., 2016)

- One should apply models directly to data!
- Example: GRB 130606B – no difference between synchrotron and Band models in terms of goodness of fitting

Band & synchrotron model fits
Gamma-ray bursts as cool synchrotron sources

J. Michael Burgess¹,², Damien Bégué¹, Ana Bacelj¹,³, Dimitrios Giannios⁴, Francesco Berlato¹,⁵, and Jochen Greiner¹,²

Here we show that idealized synchrotron emission, when properly incorporating time-dependent cooling of the electrons, is capable of fitting ~95% of all time-resolved spectra of single-peaked GRBs as measured with Fermi/GBM. The comparison with spectral fit results based on previous empirical models demonstrates that the past exclusion of synchrotron radiation as an emission mechanism derived via the line-of-death was misleading. Our analysis probes the physics of these ultra-relativistic outflows and the
Big Picture: GRB jet composition

- GRB jets have diverse compositions:
  - Photosphere dominated (GRB 090902B), rare
  - Intermediate bursts (weak but not fully suppressed photosphere, GRB 100724B, 110721A)
  - Photosphere suppressed, Poynting flux dominated (GRB 080916C)

The majority of GRBs have significant magnetization

*Gao & Zhang 2015*
Fermi/IceCube Surprise #3: Non-detection of neutrinos by IceCube

- Icecube so far has not detected any high-energy neutrino associated with GRBs!
- Consistent with a large emission radius (magnetic dissipation)
Smoking gun #1:
Spectral lags & Ep evolutions

Norris et al. (1996)

(Lu et al. 2012)
Smoking gun #1: Spectral lags & Ep evolutions

Uhm & Zhang (2016)

Uhm, Zhang & Racusin (2018)

Model requirements:
1. Large emission region
2. Bulk acceleration

\[ r \sim \Gamma^2 c \ t_{\text{pulse}} \sim (3 \times 10^{14} \text{ cm}) \Gamma_2^2 (t_{\text{pulse}}/1 \text{ s}) \.]
Bulk acceleration & “dark energy”

Energy Flow in GRBs

- Gravitational
- Spin (kinetic)

Thermal
- Magnetic dissipation
- Thermal acceleration
- Photopshere emission

Kinetic
- Magnetic acceleration
- Shock dissipation

Radiation

Smoking gun of Poynting flux dissipation: bulk acceleration in the emission region
Smoking gun #2: High-latitude emission & curvature effect

- Predicted features:
  - Lightcurve:
    \[ F_{\nu, \text{obs}} \propto t_{\text{obs}}^{-\hat{\alpha}} \nu_{\text{obs}}^{-\hat{\beta}}, \]
    \[ \hat{\alpha} = 2 + \hat{\beta}, \]
    \[ \text{Kumar} \ & \text{Panaitescu} \ (2000) \]
  - Spectral:
    \[ F_{\nu, E_p} \propto E_p^{2}. \]

Not detectable for photosphere emission
Deng \& Zhang, 2014
Curvature effect


\[ F_{\nu_{\text{obs}}} \propto t_{\text{obs}}^{-\hat{\alpha}} \nu_{\text{obs}}^{-\hat{\beta}}, \quad \hat{\alpha} = 2 + \hat{\beta}, \]

Kumar & Panaitescu (2000)

Only applies for constant Lorentz factor
Steeper with bulk acceleration, shallower with bulk deceleration
High latitude emission in X-ray flares: again bulk acceleration & Poynting flux

High-latitude emission in prompt emission

- Not easy to test the lightcurve relation
  - Overlapping
  - Not long enough tail to measure
  \[ F_{\nu_{\text{obs}}} \propto t_{\text{obs}}^{-\alpha} \nu_{\text{obs}}^{-\beta} , \]
- Direct & clean test:
  \[ F_{\nu, E_p} \propto E_p^2 \]

*Uhm et al. (2018); Tak et al. (2018)*

*Next talk by Donggeun Tak*
Summary

• The excellent GRB data collected by Fermi GBM and LAT have revolutionized our physical understanding of GRB prompt emission

• Data used:
  – Time resolved spectra: ”Band” component, thermal component, high energy component
  – Light curve spectral lags
  – Ep evolution within pulses (\( F_{\nu,E_p} \propto E_p^2 \))
  – Non-detection of neutrinos

• Conclusions drawn:
  – GRB jet composition is diverse
  – Fireballs are rare, but some GRBs (e.g. GRB 090902B) are dominated by photosphere emission
  – Most GRB outflows are Poynting-flux-dominated at least at the central engine, and are likely still moderately magnetized in the emission region
  – The emission mechanism of the “Band” component is synchrotron radiation from an optically thin region, likely invoking dissipation of magnetic energy, at least for some, possibly most, GRBs.
Future prospects with Fermi (GRB physics)

• More targeted data analysis can answer the following questions:
  – Detections / non-detections of the thermal component can systematically constrain the jet magnetization parameter;
  – Joint spectral and temporal analyses may lead to the identification of two types of GRBs (in terms of jet composition);
  – Comparison of the statistical properties of different types?
  – Short vs. long
photosphere
small-radius IS

ICMART
large-radius IS