Gamma-Ray Bursts: from Swift to GLAST Bing Zhang



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Collaborators

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Gamma-ray bursts: the most violent explosions in the universe!

Milestone 1: 1969-1973 (discovery)



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OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

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ABSTRACT

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~30 s, and time-integrated flux densities from ~ 10^{-5} ergs cm⁻² to ~ 2×10^{-4} ergs cm⁻² in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

Subject headings: gamma rays - X-rays - variable stars

Milestone 2: 1991 (CRGO era)



Milestone 3: 1997 (BeppoSAX-HETE era)



Milestone 4: 2004-2005 (Swift era)

The GRB Explorer Mission:

A Multiwavelength Observatory for Rapid-Response Observations of Transient Targets



Launched on Nov. 20, 2004

Prime institution: NASA/GSFC Leading university partner: PSU Country involved: USA, Italy, UK

Milestone 5: 2007? (GLAST era)



Purpose of the talk

How Swift revolutionized our understanding of GRBs?
Highlights of Swift discoveries
Expectations in the optical band
Surprises in the X-ray band
What can one expect in the GLAST era?

GRBs in the Swift Era

Swift discoveries - highlights

- Mystery of short-hard GRBs partially solved
- z=6.3 GRB discovered
- Extensive study of early afterglows
- Bridge between the prompt emission and the afterglow
- X-ray flares
- Tight UVOT early upper limits

Short GRB: 050509B (Gehrels et al. 2005; Bloom et al. 2005)





Short GRB: 050709 (Fox et al. 2005; Covino et al. 2005)



Z=0.16

Short GRB: 050724 (Barthelmy et al. 2005; Berger et al. 2005)



Z=0.258

Origin or short GRBs: Compact star mergers?



High-z (6.3) GRB: 050904 (Haislip et al. 2005; Cusumano et al. 2005)



What do we learn about GRB physics?

A generic GRB fireball



Why is the early afterglow essential?

- Diagnose the composition of the fireball ejecta (Baryonic or magnetic?)
 - late afterglow is the emission from the medium)
- Diagnose the immediate environment of GRBs (ISM or wind? Density clumps?)
- Diagnose the site of GRB emission (external or internal?)
- Diagnose the central engine activity (any long-lasting injection?)

Expectations in the Optical Band:

Reverse Shock Emission & Fireball Composition

GRB Composition

Baryonic component
 Protons and electrons
 Neutrons
 Magnetic fields (Poynting flux)

Answer: from Early Afterglows!

A generic GRB fireball



Early optical afterglow lightcurves

(Zhang Kohavashi & Meszaros 2003)



GRB 990123 (Akerlof et al. 1999)



 $R_B = B_r / B_f \sim 15$

Zhang, Kobayashi & Meszaros, 2003

Fan et al. 2002

GRB 021211 (Fox et al. 2003; Li et al. 2003)



$$R_B = B_r / B_f >> 1$$

Zhang, Kobayashi & Meszaros, 2003

Kumar & Panaitescu 2003

GRB 041219A (Vestrand et al. 2005; Blake et al. 2005)



Reverse shock dynamics/emission with arbitrary magnetization (Zhang & Kobayashi 2005) Data call for a more complete theory to treat **GRB** reverse shock Magnetic fields are introduced dynamically • Arbitrary $\sigma = F_P/F_k$, ratio between the Poynting flux and the baryonic kinetic flux First-order theory Assume pure MHD shocks, no magnetic dissipation Assume 90 degree magnetic fields

An analytic MHD shock Solution for GRB reverse shocks (Zhang & Kobayashi 2004)

Two free parameters:

 $\sigma, \ \gamma_{34}$

 $\sigma = 0$ Blandford-McKee (1976)







Optical, forward + reverse shock emission $2 \sim 0$







t?

t-2

Optical, forward + reverse shock emission ~ 100

Characteristics of a Poynting flux dominated flow

- (Zhang & Kobayashi 2005)
 The reverse shock emission component is significantly suppressed
- The Poynting energy is not immediately transferred to the ambient medium. The early afterglow emission is dimmer.
- The fireball is initially continuously refreshed until all the Poynting energy is transferred to the medium.

Neutron-rich fireballs & early afterglow

If GRB jets are dominated by the baryonic component, then the neutron component has an important impact on GRB afterglow lightcurves (Derishev et al. 1999; Beloborodov 2003)

 Detailed dynamical evolution & lightcurve calculation (Fan, Zhang & Wei 2005)
Characteristics of a neutron-rich fireball (Fan, Zhang & Wei 2005)

- The signature becomes important only when the neutron abundance is similar to the proton abundance;
- In the wind medium, an early optical plateau due to neutron decay trail emission is predicted, but the gammaray front overlaps with the reverse shock region, and the signature is smeared out;

In the ISM medium, a neutron-rich ejecta naturally gives rise to an "injection" signature due to the collision between the proton shell and the decelerated neutrondecay shell.

Neutron-fed fireball dynamics (ISM)

(Fan, Zhang & Wei, 2005)



GRB 041219a



 Contemporaneous IR flash & early Afterglow – PAIRITELBlake et al.
2005

 Contemporaneous optical flash tracking GRB lightcurves – RAPTOR, Vestrand et al. 2005.

Neutron-rich internal shocks & mildly magnetized reverse shock + forward shock model Fan, Zhang & Wei, 2005

GRB 050525a



- Early reverse shock
- Transition to forward shock
- Re-brightening
- Jet break

Blustin et al., 2005

UVOT Dark Bursts



Lack of reverse shock Highly magnetized flow?

Roming et al., 2005

UVOT Dark Bursts



Apparently high gamma-ray efficiency. Highly magnetized flow?

Roming et al., 2005

Surprises in the X-Ray Band:

Emission Site & Central Engine

BAT Bursts

• 73 GRBs detected/imaged since Dec. 17 (37 weeks as of 9/16/05) => 102/yr



XRT Detections of BAT GRBs

- Detected 56/59 = 95% with XRT (observed @ T < 200 ks)
 - Observed four during burst
 - 42/56 = 75% Swift detections were prompt observations (< 300 s)
 - 37/42 have fast decline or flare within first \sim 5 minutes
 - 20 have redshift measurements:
 - Average redshift: 2.2 (compared with about 1 for Beppo-SAX bursts)
 - Highest redshift: 6.29 (highest redshift GRB on Historet)



Typical XRT afterglow

(Nousek et al. 2005, ApJ, submitted)



The "oddball" cases

(Nousek et al. 2005, ApJ, submitted)



A Generic X-ray Lightcurve?

(Zhang, Fan, Dyks, Kobayashi, Meszaros, Burrows, Nousek & Gehrels 2005)



Five components

- A steep decay GRB tail emission
- A shallow-than-normal decay refreshed shock
- A normal decay a fireball with constant energy running into a medium with a constant density
- A possible jet break
- One or more X-ray flares

Although the 3rd and 4th components are expected, the other three components are surprises to GRB workers.

Rosetta Stone (the burst that has it all!)

GRB 050315 Vaughn et al. 2005



Surprise 1: Rapid Early Declines



A Generic X-ray Lightcurve? (Zhang et al. 2005)



Interpretation

Tail of prompt GRB emission or the late central engine emission – curvature effect (Kumar & Panaitescu 2000; Dyks et al. 2005)

Important implication: GRBs and afterglows come from different locations!



GRB Emission Site

Internal

- Internal shocks
- Internal magnetic dissipation
- External shock
- "Innermost" model: dissipative photosphere

Answer: the rapid decay indicates that the GRBs are of internal origin!

A generic GRB fireball



Surprise 2: Shallow-than-normal decay

050319 050416A 050713B 050721 and more



A Generic X-ray Lightcurve? (Zhang et al. 2005)



Interpretation

The best interpretation is that the fireball shock is continuously refreshed during the flat stage, so that the fireball energy increases with time until 10^3-10^4 s when the injection process ceases. There are three physical possibilities:

 The central engine is still injecting energy with a decreasing power (Zhang & Meszaros 2001)

 $L(t) \propto t^{-q}$

Data suggests $q \sim (0.4 - 0.6)$, pulsar gives q = 0

The ejecta has a power law distribution of Lorentz factors (Rees & Meszaros 1998; Sari & Meszaros 2000)

 $M(>\gamma) \propto M^{-s}$

Why there is a sharp Lorentz factor cut off? Why power law?

A Poynting-flux dominated flow, a factor of (1+σ) more energy is injected after the reverse shock disappears (Zhang & Kobayashi 2005). Why q ~ 0.5?



A Generic X-ray Lightcurve? (Zhang et al. 2005)



Giant X-ray Flare: GRB050502b



Burrows et al. 2005, Science; Falcone et al. 2005, ApJ

RS SSC bump?



Can interpret 050406, but difficult to interpret 050502b

Kobayashi et al., 2005

Density Bump?



Two Component Jets?



Patchy Shells?



Late central engine activity - late internal shocks

- Can naturally interpret rapid rise and rapid fall of the lightcurves.
- A much smaller energy budget is needed.



GRB 050502b (Falcone et al. 2005)



Flares in short GRB 050724 (Barthelmy et al. 2005)



Flares in the z=6.29 GRB 050904



What do we expect in the GLAST era?

Expected high-energy (GeV-TeV) emission from GRBs

Prompt phase

- Extended emission
 - High energy afterglow
 - Photon-pair interaction in the fireball and IC with CMB
- High energy flares?
 - IC from the X-ray flares?
 - Overlapping and wind signature

A generic GRB fireball


Prompt GeV-TeV emission (Razzaque, Meszaros & Zhang 2004)



Become opaque above 10-100 GeV, transparent again above several Pe Depends on the Lorentz factor of the fireball.

Extended Emission - Previous Observational Evidence GRB 940217 (Hurley et al. 1994) Lasted 90 minutes Hard, including one 18 GeV photon GRB 941017 (Gonzalez et al. 2003) A distinct multi-MeV spectral component Decays more slowly than the low energy component

GRB 941017 (Gonzalez et al. 2003)



Reasons to Believe Extended Emission

The synchrotron self-Compton in the external forward shock naturally gives to an extended high energy afterglow (Zhang & Meszaros 2001; Dermer et al. 2000)

The TeV photons escaping from the fireball (likely from external shock) interacts with IR background and produce pairs, which then scatter CMB to produce extended GeV emission (Dai & Lu 2002; Dai et al. 2002; Razzaque et al. 2004)

A generic GRB fireball



High Energy Afterglow (Zhang & Meszaros 2001)



Photon-Pair Interaction (Razzaque, Meszaros & Zhang 2004)



GeV flares - like X-ray flares?



GeV flares - possible but harder to detect

IC in the X-ray flares may give harder flares

Caveats:

- We haven't had solid observational evidence of the IC component in GRBs yet (quite robust in AGNs)
- The background (forward shock) component fades slowly even rises initially

X-ray flares

GeV flares

Sub-GeV flare: a wind signature (Fan, Zhang & Wei 2005)

- When fireball decelerates early enough ("thick shells"), the external shocks (forward & reverse) overlap the prompt gamma-ray flow. IC is very important (Beloborodov 2005)
- The IC gamma-rays will produce pairs, forming a photon-pair cascade. The main output is in the sub-GeV range (Fan, Zhang & Wei 2005)
- If the circumburst medium is a stellar wind, the above condition is naturally satisfied.

Conclusions

- ✓ Swift is revolutionizing our understanding of GRBs;
- Early UV/optical/IR observations may be interpreted within the simplest reverse shock + forward shock framework, but the case is inconclusive;
- Prompt emission is originated from a different site from the afterglow;
- ✓ GRB central engine is still alive after the GRB ceases.
- Theories suggest that prompt GRB emission extends to 10-100 GeV range
- Theories suggest that long-term GeV-TeV emission is expected
- ✓ GLAST may again revolutionize our understanding of GRBs