On the nature of relativistic jets in gamma-ray bursts

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Relativistic jets in gamma-ray bursts (GRBs)

- GRBs are powered by highly relativistic jets with bulk Lorentz factors of a few hundreds, which are moving toward the Earth.
- One of the most outstanding questions in the field concerns about the composition of the jets: matter dominated vs Poynting-flux dominated.

(Image credit: NASA/Swift/Mary Pat Hrybyk-Keith and John Jones)
In this talk, I will show that two independent properties of GRB observations (i.e., spectral lags and X-ray flares) provide a “smoking-gun” signature to support one of these two cases.
GRB Prompt Emission

- Prompt phase of gamma-rays exhibits diverse and complex features
- Fast variabilities are superimposed on slowly-varying “broad pulses”
- Interesting properties of broad pulses are observationally known, such as “spectral lags”

Photon count rate in units of seconds

Figure from Meszaros 2006
Spectral Lags during the Prompt Phase of GRBs

- Gamma-ray light curves at different sub-energy bands have a sequential pattern in their peaking time.
- Usually, higher energy emission has an earlier peak and a narrower width as compared to lower energy emission.

(Norris et al. 1996)
X-ray Flares in GRBs

• Unexpected in the standard theory of afterglow radiation emitted from an external blast wave
• Characteristic flaring behavior of a rapid rise followed by a steep fall, which appears to be superimposed on the underlying afterglow
• Accompanied by distinctive pattern of spectral evolution
• Hence, X-ray flares are believed to share a similar physical mechanism with GRB prompt emission
• Owing to the steep fall seen in the decay phase, the “curvature effect” is commonly invoked to account for the falling phase of X-ray flares
• This is to say, even when the emission from spherical surface of a relativistic jet ceases abruptly, the light curves as detected by a distant observer do not drop to zero immediately
• Instead, they are shaped by photons emitted from high-latitude locations
• This shaping by the “high latitude emission” obeys the relativistic Doppler boostings between the co-moving frame and the observer frame and the different arrival times depending on the latitude of emitted photons
Curvature Effect of a Relativistic Spherical Shell

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AFTERGLOW EMISSION FROM NAKED GAMMA-RAY BURSTS

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ABSTRACT

We calculate the afterglow emission for gamma-ray bursts (GRBs) going off in an extremely low density medium, referred to as naked bursts. Our results also apply to the case where the external medium density falls off sharply at some distance from the burst. The observed afterglow flux in this case originates at high latitudes, i.e., where the angle between the fluid velocity and the observer line of sight is greater than $\Gamma^{-1}$. The observed peak frequency of the spectrum for naked bursts decreases with observer time as $t^{-1}$, and the flux at the peak of the spectrum falls off as $t^{-2}$. The 2–10 keV X-ray flux from a naked burst of average fluence should be observable by the Swift satellite for a duration of about $10^3$ longer than the burst variability timescale. The high-latitude emission contributes to the early X-ray afterglow flux for any GRB, not just naked bursts, and can be separated from the shocked interstellar medium emission by their different spectral and temporal properties. Measurements of the high-latitude emission could be used to map the angular structure of GRB-producing shells.

Subject headings: gamma rays: bursts — gamma rays: theory

(Kumar & Panaitescu 2000)

- High latitude emission satisfies a simple relation $\alpha=2+\beta$ between the temporal index $\alpha$ and the spectral index $\beta$
- Convention $F_\nu \propto t^{-\alpha} \nu^{-\beta}$
X-ray Flares and “t₀ Effect”

- Left panel to show a cartoon picture of Swift XRT light curves
- In most cases, the decay phase of X-ray flares is significantly steeper than the prediction $\alpha=2+\beta$
- Right panel to demonstrate the so-called “t₀ effect” on the light curves that are plotted in logarithmic scales
- Same emission episode but with different ejection times appears to have different decay slopes

(Zhang et al. 2006)
Curvature Effect of a Relativistic Spherical Shell

(Uhm & Zhang 2015)

- High latitude emission satisfies $\alpha=2+\beta$ (for convention $F_\nu \propto t^{-\alpha} \nu^{-\beta}$) only when the Lorentz factor $\Gamma$ is constant.
- In the case of an accelerating shell, the light curves made by the high latitude emission are significantly steeper than the constant $\Gamma$ case.
- The trend is opposite for a decelerating shell.
Evidence of Bulk Acceleration in Three Example X-ray Flares

(Uhm & Zhang 2016a)

- Choose the maximum possible value of $t_0$ (i.e., the most conservative one) as shown by the dotted vertical line
- Construct the green decay curve based on the prediction $\alpha=2+\beta$
- X-ray flares are produced while their emitting region is undergoing rapid bulk acceleration
Numerical Modeling for the Three X-ray Flares

(Uhm & Zhang 2016a)

- Perform numerical calculations to model both the X-ray flare light curves and the photon index evolution curves within a simple physical model that invokes the synchrotron radiation emitted from a bulk-accelerating emission region.
- For $\Gamma \propto r^s$, $s = 1.15$, 0.95, and 0.8 for the three X-ray flares, respectively.
Statistical Study of 85 Bright X-ray Flares Detected in 63 GRBs

(107x88 to 615x497)

• 56/85 flares (method I) or 74/85 flares (method II) are in the acceleration regime at 99.9% confidence level

(Jia, Uhm & Zhang 2016)
• Photons from higher latitude take longer time to reach the observer
• Relativistic beaming of radiation at higher latitude has progressively smaller Doppler boosting in the direction of the observer
• Hence, the curvature effect indicates a possibility to agree with basic properties of spectral lags
One popular idea to account for the observed spectral lags invokes the high–latitude emission from a relativistic spherical surface.
Curvature Effect Cannot Account for Observed Spectral Lags

Curvature effect of the high-latitude emission is fully taken into account.

No spectral lags are possible for a physical spectrum wider than the Planckian function.

(Uhm & Zhang 2016b)
Fast-cooling synchrotron radiation in a decaying magnetic field and $\gamma$-ray burst emission mechanism

Z. Lucas Uhm$^{1,2}$ and Bing Zhang$^{1,2,3\ast}$

Synchrotron radiation of relativistic electrons is an important radiation mechanism in many astrophysical sources. In the sources where the synchrotron cooling timescale is shorter than the dynamical timescale, electrons are cooled down below the minimum injection energy. It has been believed that such 'fast cooling' electrons have a power-law distribution in energy with an index $-2$, and their synchrotron radiation has a photon spectral index$^1$ $-1.5$. On the other hand, in a transient expanding astrophysical source, such as a $\gamma$-ray burst (GRB), the magnetic field strength in the emission region continuously decreases with radius. Here we study such a system, and find that in a certain parameter regime, the fast-cooling electrons can have a harder energy spectrum. We apply this new physical regime to GRBs, and suggest that the GRB prompt emission spectra whose low-energy photon spectral index has a typical value$^{2,3} -1$ could be due to synchrotron radiation in this moderately fast-cooling regime.

Injection Lorentz factor $\gamma_m$ of the electrons. For synchrotron radiation, the electron energy loss rate is

$$\dot{\gamma} = -\frac{\sigma_T B^2 \gamma_e^2}{6 \pi m_e c} \propto -\gamma_e^2 B^2$$

where $\sigma_T$, $m_e$ and $c$ are Thomson cross-section, electron mass and speed of light, respectively, and $B$ is the strength of magnetic fields in the emission region. For fast cooling, electrons are cooled rapidly to an energy $\gamma_e(t)$ (cooling energy) below the injection energy $\gamma_m$ at time $t$. In the regime $\gamma_e < \gamma_m < \gamma_w$, one has $Q(\gamma_e, t) = 0$. Also consider a steady-state system ($\partial/\partial t = 0$), then one immediately gets $dN_e/d\gamma_e \propto \gamma_e^{-2}$; that is, the electron spectral index is $\dot{\gamma} = 2$. The specific intensity of the synchrotron spectrum would have a spectral index$^3$ $s = (\dot{\gamma} - 1)/2 = 1/2$ (with the convention $F \propto \nu^{-s}$). The photon spectral index (defined as $dN_\nu/dE_\nu \propto E_\nu^s$, where $E_\nu$ is the photon energy, and $N_\nu$ is the photon number flux) would then

(Uhm & Zhang 2014)

- As a conical jet propagates in space, the strength of magnetic fields in the emitting region should globally decrease in radius: $B(r) \propto r^{-b}$
Photon Spectrum

- \( B(r) = B_0 \left( \frac{r}{r_0} \right)^{-b} \) with \( B_0 = 30 \text{ G} \) and \( r_0 = 10^{15} \text{ cm} \)
- \( b = 0, 1, 1.2, 1.5 \) for Models [a], [b], [c], and [d], respectively

(Uhm & Zhang 2014)
### Table 1 | Spectral parameters of models [e], [b], [f] and [g] (constant injection rate).

<table>
<thead>
<tr>
<th>Model</th>
<th>$B'_0$ (G)</th>
<th>$t_{obs}$ (s)</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$E_p$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[e]</td>
<td>10</td>
<td>1</td>
<td>-1.03</td>
<td>-2.13</td>
<td>480</td>
</tr>
<tr>
<td>[e]</td>
<td>10</td>
<td>3</td>
<td>-1.03</td>
<td>-2.10</td>
<td>220</td>
</tr>
<tr>
<td>[b]</td>
<td>30</td>
<td>1</td>
<td>-1.22</td>
<td>-2.26</td>
<td>490</td>
</tr>
<tr>
<td>[b]</td>
<td>30</td>
<td>3</td>
<td>-1.17</td>
<td>-2.26</td>
<td>220</td>
</tr>
<tr>
<td>[f]</td>
<td>100</td>
<td>1</td>
<td>-1.42</td>
<td>-2.33</td>
<td>590</td>
</tr>
<tr>
<td>[f]</td>
<td>100</td>
<td>3</td>
<td>-1.39</td>
<td>-2.35</td>
<td>240</td>
</tr>
<tr>
<td>[g]</td>
<td>300</td>
<td>1</td>
<td>-1.50</td>
<td>-2.34</td>
<td>650</td>
</tr>
<tr>
<td>[g]</td>
<td>300</td>
<td>3</td>
<td>-1.50</td>
<td>-2.37</td>
<td>250</td>
</tr>
</tbody>
</table>

We then find the solution of electron Lorentz factor at any time $t'_j > t'_i$

$$\gamma_s(t'_j) = \left[ \frac{1}{\gamma_s(t'_i)} + \frac{a}{1-2b} \left\{ t'_j^{1-2b} - t'_i^{1-2b} \right\} \right]^{-\frac{1}{b-1}}$$

where $\gamma_s(t'_i)$ is the electron Lorentz factor at an initial time $t'_i$. For $b > 1/2$, $t'_j \gg t'_i$, and $\gamma_s(t'_j) \ll \gamma_s(t'_i)$, this solution gives $\gamma_s(t'_j) \propto t'_j^{2b-1}$. We then get

$$\delta N_e \propto t'_j^{2b-2} \delta t'_i \propto \left[ \gamma_s(t'_i) \right]^{\frac{2b-3}{b-1}} \delta t'_i$$

For a constant injection rate $R_{inj}$, we have $\delta N_e \propto \delta t'_i$. Thus, we have an asymptotic behaviour of the global electron spectrum as follows.

$$\frac{\delta N_e}{\delta \gamma_s(t'_j)} \propto \left[ \gamma_s(t'_i) \right]^{-\frac{2b-3}{b-1}}$$

Now we consider the full equation (2) that includes the adiabatic term. For $B'(r) = B'_0 (r/r_0)^{-q}$ and $r = c t' T'$, equation (2) can be written as

(Uhm & Zhang 2014)
Magnetic Field Strength in the Emitting Region Should Decrease

- Strength of magnetic fields in the shell should decrease in radius: $B(r) \propto r^{-b}$
- Index $b = 1.0, 1.25, \text{ and } 1.5$ for the models [1b], [1c], and [1d], respectively

(Uhm & Zhang 2016b)
Emitting Region Itself Should Undergo Bulk Acceleration

- In addition to the decreasing profile of $B(r) \propto r^{-b}$, the emitting region itself should undergo rapid bulk acceleration: $\Gamma(r) \propto r^s$
- Index $b = 1.0, 1.25, \text{and} 1.5$ for the models [2b], [2c], \text{and} [2d], respectively
- Index $s = 0.35$ for all three models

(Uhm & Zhang 2016b)
Observed Properties of Spectral Lags

- Upper panel is to show the peak time vs. the frequency of each light curve for the six different models.
- Lower panel is to show the width vs. the frequency of each light curve.
- It is clear that the models without bulk acceleration are inconsistent with the observed properties of spectral lags.
- Hence, bulk acceleration is again required to explain the spectral lags.

(Uhm & Zhang 2016b)
Dark Energy in GRBs?

- In a sense, this bulk acceleration reminds us of our universe’s accelerated expansion due to ‘dark energy.’
- Unlike in cosmology, we have a good candidate for “dark energy” in relativistic jets in GRBs, namely, a Poynting flux energy carried by the jets.
GRB jets are Poynting–flux dominated

- Acceleration due to internal energy of “fireball” explosions proceeds early at small radii since an adiabatic conversion of thermal energy into kinetic energy of bulk motion follows $\Gamma \propto r$ (Meszaros et al. 1993)
- After this phase, there is no other good candidate besides a Poyting flux energy
- Matter dominated jets make use of kinetic energy to power GRBs
- Part of dissipated Poynting–flux energy can be used to accelerate the bulk flow
- Therefore, required bulk acceleration in the emission region provides a “smoking-gun” signature of a Poynting–flux dominated jet in GRBs
Summary

• Standard simple relation $\alpha=2+\beta$ (between the temporal index $\alpha$ and the spectral index $\beta$) of the high latitude emission is significantly deviated for an accelerating or decelerating shell.

• Steep decay phase of GRB X-ray flares provides a clear observational evidence that the X-ray flare jets undergo rapid bulk acceleration in their emitting region.

• Spectral lags and their observed properties during the prompt phase require that the emitting region of GRB prompt emission jets should undergo bulk acceleration as well.

• Requirement of bulk acceleration in GRB prompt emission and X-ray flares points toward a significant Poynting flux carried by relativistic jets in GRBs.
Equal Arrival Time Surface (EATS)

- Photons emitted from EATS are received by the observer simultaneously.
- EATS has an ellipsoidal shape for a constant Lorentz factor.
• Departure from the relation $\alpha=2+\beta$ depends most sensitively on how fast the Lorentz factor $\Gamma$ increases or decreases.

(Uhm & Zhang 2015)
Testing the Curvature Effect while Incorporating the $t_0$ Effect

Using an average value of measured photon indices and based on the prediction $\alpha=2+\beta$ of the curvature effect, the authors search for a best fit value of $t_0$ that is required to give a good fit to the steep decay phase of X-ray flares.

As shown by the blue vertical lines, the required value of $t_0$ is indeed associated with the location of X-ray flares.
• Early acceleration due to internal energy of “fireball” explosions proceeds at small radii since an adiabatic conversion of thermal energy into kinetic energy of bulk motion follows $\Gamma \propto r$ (Meszaros et al. 1993)

• Required bulk acceleration in the emission region provides a “smoking-gun” signature of a Poynting flux dominated outflow