X-ray & $\gamma$-ray Polarization in Gamma-Ray Bursts

Jonathan Granot

Institute for Advanced Study, Princeton

X-ray Polarimetry Workshop
KIPAC, February 10, 2004
Outline of the Talk:

- Short Overview of GRBs
- Why is GRB polarization interesting
- GRB polarization: an unresolved relativistic jet
- Polarization of the prompt γ-ray emission: theoretical expectations (relatively in detail)
- Polarization of early X-ray afterglow (brief)
- Conclusions
Observations: Prompt GRB

- Variable light curve

- Duration: $\sim 10^{-2} - 10^3$ sec

- Spectrum: non-thermal

  - $\nu F_\nu$ peaks at $E_p \sim 0.1 - 1$ MeV
  
  - $E_p \propto (E_{\gamma,\text{iso}})^{1/2}$ (Amati et al. 03)

- Rapid variability, non thermal spectrum & $z \sim 1$

  $\Rightarrow$ relativistic source ($\Gamma \sim 100$) (compactness problem: Schmidt 1978; Fenimore et al. 1993; Woods & Loeb 1995; ...
Observations: Afterglow

- X-ray, optical & radio emission over days, weeks & months, respectively, after a GRB
- **Spectrum:** consists of several power law segments & is well fit by *synchrotron* emission

GRB 970508
Spectrum at 12.1 days
(Galama et al. 1998)
Light curve: power law decay; some afterglows show an achromatic steepening of the light curve (‘jet break’)

\[ z \sim 1 + \text{fluence} \Rightarrow \text{energy output in } \gamma\text{-rays:} \]

- assuming isotropic emission: \( E_{\gamma, \text{iso}} \sim 10^{52}-10^{54} \text{ erg} \)
- correcting for a jet: \( E_{\gamma} \sim 10^{51} \text{ erg} \)

Optical light curve of GRB 990510 (Harrison et al. 1999)

X-ray light curves of several GRBs (Piro 1999)
Theory: Fireball vs. Poynting Flux

Compact Source

Promp GRB

Internal Shocks

Particle acceleration
⇒ synchrotron \( \gamma \)-rays

reconnection
(or other EM instability)

Magnetic bubble

Lyutikov & Blandford 02,03

Afterglow

X-rays
Optical
Radio

External medium

X-rays
Optical
Radio

Prompt GRB

E_{\text{kin}}

E_{\text{EM}}

Matter dominated

outflow

E_{\text{kin}}

E_{\text{EM}}

Poynting flux

dominated flow

† Shemi & Piran 90,
Goodman 86,
Paczynski 86,…

‡ Meszaros & Rees 92,
Katz 94, Sari & Piran 95

†† Shemi & Piran 90,
Goodman 86,
Paczynski 86,…

Thompson & Piran 90,
Thompson 94, Usov 94,
Meszaros & Rees 97,
Katz 97,…

††† Lyutikov & Blandford 02,03

Reconnection

E_{\text{EM}}

E_{\text{kin}}
Why is GRB Polarization Interesting

- It teaches us about the magnetic field structure in the GRB ejecta & provides clues as to whether most of energy is in Poynting flux or kinetic energy:
  - $E_{EM} \gg E_{kin} \implies$ ordered magnetic field is expected
  - $E_{kin} - E_{EM} \implies$ ordered & random fields are possible
- Provides a strong test for the structure of GRB jets, both in the prompt GRB & in the afterglow
- Probes magnetic field structure behind afterglow shock
- Helps pin down cause of time variability in afterglows
Polarization of Synchrotron Emission

Linear polarization perpendicular to the projection of $\mathbf{B}$ on the plane of the sky

The maximal polarization is for the local emission from an ordered $\mathbf{B}$-field: $P_{\text{max}} = (\alpha+1)/(\alpha+5/3)$ where $F_\nu \propto \nu^{-\alpha}$, $-1/3 \leq \alpha \leq 1.5 \Rightarrow 50\% \leq P_{\text{max}} \leq 80\%$

(Rybicki & Lightman 1979; Granot 2003)
Shock Produced Magnetic Field:

- A magnetic field that is produced at a relativistic collisionless shock, due to the two-stream instability, is expected to be tangled within the plane of the shock (Medvedev & Loeb 1999)

\[ P = \frac{P_{\text{max}} \sin^2 \theta}{1 + \cos^2 \theta} \]

(Liang 1980)

\[ n_{\text{ph}} = n_{\text{sh}} \]

Photon emitted normal to plane

Photon emitted along the plane
Relativistic source:

The observer sees mostly emission from within an angle of \(1/\Gamma\) around the l.o.s.
Polarization in the observer frame

Random field in shock plane

Ordered field in shock plane

-2 -1.5 -1 -0.5 0 0.5 1 1.5 2

Sari 99; Ghisellni & Lazzati 99

Granot & Königl 03

$P \sim P_{\text{max}}$
Polarization of Prompt $\gamma$-ray emission:

GRB 021206 \( P = 80\% \pm 20\% \) (Coburn & Boggs 2003)

Extremely bright GRB, 18° from the sun \( \Rightarrow \) favorable for measuring polarization with RHESSI

However: this result is controversial

Rutledge & Fox (2003) claim:
A factor of \(~10\) less relevant photon scattering events in the detector \( \Rightarrow \) \( P \) cannot be constrained

There is an ongoing controversy
(stay tuned for the next two talks)
Polarization of prompt $\gamma$-ray emission: Theoretical Expectations

- Shock produced B-field + $\theta_{\text{obs}} - \theta_j - 1/\Gamma \Rightarrow P \approx 0$
- $P \sim P_{\text{max}}$ can be achieved in the following ways:
  1. ordered magnetic field in the ejecta,
  2. special geometry: $\theta_j < \theta_{\text{obs}} - \theta_j + 1/\Gamma \Rightarrow$ narrow jet: $\theta_j - 1/\Gamma$ (works with a shock produced magnetic field)

Waxman (2003)
Ordered Magnetic Field in the Ejecta:

- Total emission from jet
- Afterglow: instantaneous emission
- Prompt GRB: time integrated emission

\( F \propto \nu^{-\alpha}, \) \( P \) increases with \( \alpha \)

\( \nu P \) from an ordered B-field is slightly larger in afterglow

Granot & Königl 03 (Granot 2003)
Narrow Jet + shock produced B-field

- High polarization + reasonable flux $\Rightarrow \theta_j < \theta_{\text{obs}} - \theta_j + 1/\Gamma$
- A reasonable probability for such $\theta_{\text{obs}} \Rightarrow \Gamma \theta_j \sim \text{a few}$
- Since $\Gamma \sim 100$ & $\theta_j \sim 0.05$, $\Gamma \theta_j \sim 5$ and is typically larger
- However GRB 021206 was very bright, suggesting a very narrow jet: $f = 1.6 \times 10^{-4}$ erg which for $z \sim 1$ implies $E_{\text{iso}} \sim 10^{54}$ erg & $\theta_j \sim (10^{51} \text{erg}/E_{\text{iso}})^{1/2} \sim 0.03$ (Frail et al. 01)
- $\Rightarrow \Gamma \theta_j \sim 3(\Gamma/100) \Rightarrow \Gamma \theta_j \sim \text{a few is possible}$ (Waxman 03)
- The jet must have sharp edges: $\Delta\theta_j \sim 1/4\Gamma$ (Nakar et al. 03)
- A ‘structured jet’ produces low polarization ($\text{several } \%$)
- Most GRBs are viewed from $\theta_{\text{obs}} < \theta_j$ and are expected to have a very low polarization in this scenario
Random B-field in sock plane

\[ y_j \equiv (\Gamma \theta_j)^2 \]

\[ F_v \propto v^{-\alpha} \]

\[ \nu \Delta \Gamma \sim \Gamma \] between different shell collisions (different pulses in GRB light curve) reduces \( P \) by a factor \( \sim 2 \)
<table>
<thead>
<tr>
<th></th>
<th>Ordered Field</th>
<th>Narrow Jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P \sim 80%$</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$P \sim 50%$</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>$P \sim 25%$</td>
<td>with $B_{\text{rnd}} &lt; B_{\text{ord}}$</td>
<td>✓</td>
</tr>
<tr>
<td>$P \sim 10%$</td>
<td>with $B_{\text{rnd}} &gt; B_{\text{ord}}$</td>
<td>with $B_{\text{rnd}} &lt; B_{\perp}$</td>
</tr>
<tr>
<td>Statistics</td>
<td>High $P$ in all GRBs</td>
<td>Low $P$ in most GRBs</td>
</tr>
<tr>
<td>Optical flash</td>
<td>High $P$ - similar to the prompt GRB</td>
<td>Similar to prompt GRB (low $P$ in most GRBs)</td>
</tr>
<tr>
<td>Potential problems</td>
<td>Some $B_{\text{rnd}}$ required for Fermi acceleration</td>
<td>$\Gamma \theta_j$ a few, $\Delta \Gamma \sim \Gamma$, $B_{\text{rnd}}$ (afterglow obs.)</td>
</tr>
</tbody>
</table>
Temporal evolution of Polarization within a pulse in the GRB light curve:

Ordered B-field:

(Nakar, Piran & Waxman 2003)

Random field in shock plane:

‘short pulse’ (ΔR<R)  ‘long pulse’ (ΔR>R)
Position Angle in Different Pulses:

- In the **internal shocks** model, the polarization position angle $\theta_p$ is expected to remain constant between different pulses in the GRB light curve, both for $B_{\text{ord}}$ or narrow jet+shock produced field.

- For the **external shocks** model $\theta_p$ is expected to vary between different the pulses.
Alternative to Synchrotron: Compton Drag
(Bulk Inverse Compton Scattering of External photons)

(Lazzati et al. 2003; Dar & De Rujula 2003, Eichler & Levinson 2003)

- Requires a special geometry and/or viewing angle,
  \[ \theta_j < \theta_{\text{obs}} < \theta_j + 1/\Gamma \]
- Similar polarization properties as a shock produced B-field with one relative advantage: the local polarization \[ P = (1 - \cos^2 \theta)/(1 + \cos^2 \theta) \] can reach up to 100% while \[ P_{\text{max}} \sim 70\% \] for synchrotron
- Shares drawbacks of shock produced field + narrow jet
- It has additional problems, unrelated to polarization:
  - Explaining the prompt GRB spectrum
  - Supplying external photons for all the ejected shells
  - High photon density \( \Rightarrow \) small radii \( \Rightarrow \) high \( \tau_{\gamma\gamma} \)
Linear polarization at the level of $P \sim 1\%-3\%$ was detected in several optical afterglows. In some cases $P$ varied, but usually $\theta_p \approx \text{const}$. Different from predictions of uniform or structured jet.

Afterglow Polarization: Observations

(Covino et al. 1999)

(Gorosabel et al. 1999)
Afterglow Polarization: Theory

the polarization is usually attributed to a jet geometry

**Ordered B-field**: 
\[ \theta_p = \text{const} \]

\[ P(t \ll t_j) \sim P(t \sim t_j) \]

while for jet models 
\[ P(t \ll t_j) \ll P(t \sim t_j) \]

*Granot & Königl 03*

**Uniform jet**: 
\[ \theta_p \text{ flips by } 90^\circ \text{ at } t_j \]

(Sari 99; Ghisellini & Lazzati 99)

†Rhoads 97, 99; Sari et al. 99, …

**Structured jet**: 
\[ \propto \theta^{-2} \]

(ROSSI et al. 2003)

†† ††Postnov et al. 01; Rossi et al. 02; Zhang & Meszaros 02
Conclusions:

- **Ordered magnetic field** in the ejecta naturally produces $P \sim 30\%-65\%$, for all GRBs (all $\theta_{obs}$) & reverse shock.

- $P$ should increase with the spectral index $\alpha$ ($F_\nu \propto \nu^{-\alpha}$).

- Narrow jet + shock produced B-field or Compton drag naturally produce $P \sim 20\%-30\%$ for $\theta_j < \theta_{obs} - \theta_j + 1/\Gamma$.

  but for most GRBs $\theta_{obs} - \theta_j$ and $P \approx 0$

- The temporal evolution of $P$ within a single pulse can help distinguish between **ordered B-field** & a shock produced B-field or Compton drag.

- The pol. position angle $\theta_p$ in different pulses can help distinguish between **internal** & **external** shocks.

- Polarization measurements in early X-ray afterglow can test the GRB jet structure & the possible role of **ordered magnetic field** component: $P(t \ll t_{jet}) \sim P(t \approx \infty)$. 