Early Afterglow Polarization

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Outline

• GRB Jets: the energy content

• Why Early Afterglow Polarimetry?

• How Polarized Emission explained? Implications?
  – Onset of Afterglow, Radio flares

• Early Afterglow Polarization measurements
  – So far, and what is available soon?
Synchrotron Shock Model

1) Relativistic Outflow
2) Strong Magnetic Fields

Prompt emission: $B \sim 10^6$ Gauss
Afterglow: $B \sim 1$ Gauss
Interstellar, intercluster: $10^{-9} \sim 10^{-6}$ Gauss
Jet Models

• **Baryonic jets**
  – Fireball, Thermal pressure
  – Tangled magnetic fields generated locally by instabilities in shock.

Zhang & Meszaros 2004; Piran 2005
Medvedev & Loeb 1999; Nishikawa et al. 2003; Spitkovsky 2008

• **Magnetized jets**
  – Rotating BH system, Magnetic pressure
  – Threaded with globally ordered B-fields

Drekhahn & Spruit 2002; Lyutikov 2006; Giannios 2008; Mimica et al. 2009;
Zhang & Yan 2011; Narayan et al. 2011; Granot 2012
How to examine the energy content of GRB jets?

1) Early Afterglow modeling
   • Forward Shock – Reverse Shock modeling

2) Polarization measurements
   • Prompt Emission, Early Afterglow
1) Early Afterglow Modeling

Fan et al. 2002; Zhang, SK, Meszaros 2003; Kumar & Panaitescu 2003; Gomboc et al. 2008; Harrison & SK 2012

The relative strength between forward and reverse shock emission in early afterglow reflects magnetic energy densities in the two shock regions.

Talk by Rich Harrison on Wednesday Morning
2) Polarimetry

• Synchrotron emission is intrinsically polarized
  – with a suitable geometry/B-field structure

• Two jet models predict different structures
  – Baryonic: highly tangled, Magnetized: ordered

• Polarization measurements of synchrotron emission from GRB jets (ejecta)
Why Early Afterglow Polarimetry?

- Multi-band, wide time-span observations are important to fully understand GRB jet physics.

  Talks by Toma and Wiersema

- Early Afterglow radiated from the original ejecta
  - Late time afterglow: blast wave (shocked ISM)

- Technically easier to carry out
  - Compared to gamma-ray/X-ray polarimetry
    Kalemci et al. 2007; McGlynn et al. 2007; Gotz et al. 2009; Yonetoku et a. 2011
Emission from the original ejecta

GRB engine

- Relativistic Ejecta
  - Prompt gamma-rays
  - Optical flashes
  - Radio flares
  - X-ray flares

- Blast wave (Shocked ISM)
  - Late time afterglow

Reverse Shock
Forward Shock

Observational/Technical issues

- **Gamma-ray/X-ray polarimetry**
  - An interesting, active research field
    GAP, POET, GEMS, PoGOLite…

- **Optical Polarimetry**
  - Less challenging, but rapid follow-up needed.
  - Polarization standard stars
    - To remove the instrumental polarization, and calibrate instrumental depolarization.
  - Other photon sources in the same field
Thee main explanations for polarized prompt emission/afterglow

- Large scale, Coherent B-fields in an emission region
  - Viewing angle just outside the sharp edge of a jet
  - Emission region contains many patches of coherent B-fields

Ghisellini & Lazzati 1999; Sari 1999; Gruzinov & Waxman 1999; Granot 2003; Nakar et al. 2003; Rossi et al. 2004; Lazzati 2006; Toma et al. 2009 ...
b) Off-Axis Model

Even if magnetic fields are tangled, some degree of alignment is expected if the shock front is observed edge-on (e.g. Medvedev&Loeb 1999).
Relativistic aberration

Shock frame: $\theta' = \pi/2$

$\Rightarrow$ Lab frame: $\theta = 1/\Gamma$

Visible region region:

$\theta \approx 1/\Gamma$

a narrow jet, $\theta_j \Gamma \leq$ a few, required to have a reasonable probability of viewing the jet at an appropriate angle
Visible region contains many patches of coherent magnetic fields

Each patch contributes polarization degree and angle

The net polarization is reduced by a factor of $\sqrt{N}$.

Mildly polarized (<10%) with fluctuations of the polarization angle

Gruzinov & Waxman 1999
The first two (large scale B-fields, off-axis models) potentially can explain high polarization degree (tens %). Polarization angle does not change.

The patchy model: $P < 10 \%$;
Jumps in polarization angle
Early afterglow phase

• Dynamics of Emitters
  – Smoother flow in early afterglow phase
  – Ejecta and Shocked Ambient

• Current Optical Polarization measurements
  – Single exposures

• Measuring temporal evolution of polarization degree and angle
  – Pin down the magnetic structure of GRB jets
  – A clue to understand the jet acceleration
Liverpool telescope (with RINGO polarimeter)

• 2m robotic telescope at La Palma
GRB 060418
P < 8%

1) No large scale field in the jet
FS:50%, RS:50%

2) Strong B-field in the jet
FS:100%

GRB 090102
Detection: P=10%

Large scale field in fireball

RINGO: a single P measurements for each burst (RINGO1)

Just at the onset of afterglow
Mundell et al. 2007

In the steep decay phase
Steele et al. 2009
GRB 090102

P~10% at 160 sec in the steep decay phase

Steele et al. 2009

Gendre et al. 2010

$F_v \sim t^{-1.5}$

$F_v \sim t^{-1}$
a  Large scale, Coherent B-fields in an emission region

b  Viewing angle just outside the sharp edge of a jet

c  Emission region contains many patches of coherent B-fields
$\theta_{\text{visible}} \approx 1/\Gamma$
~10% Polarization

- Large scale B-fields exists in the ejecta.
- It is not as high as a simple model predicts P~tens %.
  - RS+FS
  - Ordered + tangled B-fields
  - Toroidal B-fields + viewing angle
  - …
P~10% at 160sec

Harrison & SK in prep
Large scale $B$-Fields + random $B$-Fields

\[
\frac{\langle B^2_{\text{coherent}} \rangle}{\langle B^2_{\text{coherent}} \rangle + \langle B^2_{\text{random}} \rangle}
\]
Toroidal field dominates at the emission radii.

Polarization angle does not change with time.

\[
\theta_{\text{visible}} \approx \frac{1}{\Gamma}
\]

The radial component \( B_r \) decays faster than the toroidal component \( B_\phi \).

Toroidal field dominates at the emission radii.

Polarization angle does not change with time.
Homogeneous fields

Harrison & SK in prep
Radio Flares

- **Reverse shocked ejecta:**
  - adiabatically cooled, radiates at lower and lower freq
  - The emission peaks in the radio about 1 day after GRB
  - Many flare events observed in radio (private communication with Frail, Kulkarni)

![Graphs showing GRB 990123 and optical flux density over time](image-url)
Limits on P of Radio Flares

Granot & Taylor 2005

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<th>GRB</th>
<th>$t$ (days)</th>
<th>$t_j$ (days)</th>
<th>$\Pi_L$</th>
<th>$\Pi_C$</th>
<th>$F_\nu$ ($\mu$Jy)</th>
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<td>$&lt;9%$</td>
<td>$715 \pm 25$</td>
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<td>$&lt;11%$</td>
<td>$&lt;19%$</td>
<td>$492 \pm 29$</td>
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VLA observations at 8.46GHz
Prompt, Optical Flashes and Radio flares

• **Lorentz factor of Ejecta**
  – Prompt, optical flash (onset of AG): $\Gamma_0 \sim 100$
  – Radio flares (1day): $\Gamma \sim 10$

• **A significant fraction of the jet visible at 1day**
  – Observed $P$ is an effective average value over the visible region.

• **Jet break at $\sim 1$day**
  – a lateral expansion of the jet
Implications/predictions

• Off-axis model

Due to the lateral expansion, the jet would occupy our line of sight at 1 day. This could reduce the polarization of the radio flare.
• Patchy model

Prompt, Early Afterglow phase

\[ \theta_B > \frac{1}{\Gamma_0} \]

Very high polarization at early times
• Patchy model

Radio flares

\[ \theta_B \ll 1/\Gamma_0 \]

Polarization significantly reduced

\[ P = \frac{P_{\text{max}}}{\sqrt{N}} \]

\[ 1/\Gamma \gg 1/\Gamma_0 \]
Polarization in Early Forward Shock Emission?
Kanata 1.5m telescope, Hiroshima, Japan

Patchy model: MHD instabilities? Density fluctuations in ambient medium

$F_{opt} \propto t^{-0.75}$

$P = 10.4 \pm 2.5\%$

$\tau = 149-706s$

Uehara, Toma, Kawabata et al. 2012
Jet break and Polarization Evolution

Figure 3. Polarization curves from a top-hat jet with shock-generated magnetic field. Different colors show polarization for different viewing angles in units of the jet opening angle. All curves but the one with $\theta_o = \theta_j$ have two polarization peaks. The polarization angle in the two peaks is rotated by 90 degrees. The black curve has only one peak that has the same orientation of the second peak of the other curves.
Density fluctuations in ambient medium

Patchy model
\[ P \sim 70\% / \sqrt{N} \]
\[ P = 10\% \rightarrow N \sim 50 \ (P/10\%)^{-2} \]

Coherent patch at \( t=300s \)
\[ l_p \sim (R/\Gamma)/\sqrt{N} \sim 4 \times 10^{14} \ E_{52}^{1/8} n_0^{-1/8} (P/10\%) \ cm. \]
\[ P \propto 1/\sqrt{N} \propto l_p(R/\Gamma)^{-1} \propto l_p E^{-1/8} n^{1/8} t^{-5/8}. \]

Temporal changes of the polarization degree and angle
\[ p \sim 0.3\% \text{ at } t = 1\text{day} \]

Late time: a few %  Covino et al. 1999; Wijers et al. 1999
P=9.9% at 1.3 day

Bersier et al. 2003
RINGO/RINGO2 use a rotating polaroid

It is possible to measure temporal evolution of polarization degrees and angles.

There are ~10 that have been observed with RINGO/RINGO2 for which we have measurements or meaningful upper limits.
GRB 110205A

Cucchiara et al. 2011

Cloud: P<16% at t=243s-
P=3.6% at ~1hr
P=1.4% at 3-4hrs
GRB 120308A

Liverpool telescope team in prep
RINGO3

- **Three cameras:**
  - Red: 760-1000 nm
  - Green: 650-750 nm
  - Blue: 350-640 nm

- **Polaroid** rotates at 1 Hz;
  8 images obtained per rotation.
RINGO2 sensitivity chart

- $R=11$
- $R=13$
- $R=15$
- $R=17$

Polarimetric Accuracy (%) vs. Exposure Time (seconds)
GRB 130408A is the first burst for which we have observed with RINGO3

Measuring temporal evolution of polarization degrees and angles in three bands
Summary

• GRB Jets: the energy content
  – How jets accelerated and collimated?
  – The origin of strong B-fields

• Why Early Afterglow Polarimetry?
  – Emission from the original ejecta

• How Polarized Emission explained? Implications?
  – Onset of Afterglow, Radio flares
  – Each model predicts different temporal behavior of polarization degree and angle. Wide time-span measurements

• Early Afterglow Polarization measurements
  – Liverpool, Kanata, MASTER, OPTIMA telescopes,….
  – Later times: larger telescopes (e.g. VLT)
  – High energy Polarimetry