Polarization in Gamma-Ray Bursts

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Outline of the Talk:

- Polarization of synchrotron rad. from a relativistic source
- Afterglow: Jet structure & dynamics, B-field structure (ES)
  - Top hat vs. structured jet
  - Shock-produced vs. ordered B-field, or combining the two
  - Shock-produced B-field’s degree of anisotropy
- Reverse shock: optical flash & radio flare (ejecta B-field)
- Prompt GRB: emission mechanism, Jet structure, ejecta B
  - High \textbf{P}: Syn. + ordered B vs. sharp jet + special viewing angle
  - Different emission mechanisms
  - What can be learned from single GRBs or a large sample
- Conclusions
**Polarization of Synchrotron Emission**

- **linear polarization** is perpendicular to the projection of **B** on the plane of the sky (normal to the wave vector)

- The maximal polarization is for the local emission from an ordered **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)
In the source rest frame:

- A uniform field produces $P = P_{\text{max}}$
- For a field random when projected on the plane of the sky: $P = 0$
- In particular, for a field isotropically tangled in 3D: $P = 0$
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).

\[ P = 0 \]

\[ P = P_{\text{max}} \sin^2 \theta / (1 + \cos^2 \theta) \] (Liang 1980)

Magnetic field tangled within a (shock) plane.

Photon emitted normal to plane
\[ n_{\text{ph}} = n_{\text{sh}} \]

Photon emitted along the plane
\[ n_{\text{ph}} \perp n_{\text{sh}} \]
Relativistic Source:

Random field in shock plane

Ordered field in shock plane

Sari 99; Ghisellini & Lazzati 99

Granot & Königl 03

$P \sim P_{\text{max}}$
Afterglow: Two “Traditional” Jet Structures

Uniform (top hat) jet:
(Rhoads 97,99; Sari+99, ...)

Log($dE/d\Omega$) vs. $\theta$

No sideways Expansion (Ghisellini & Lazzati 1999)

Fast sideways Expansion (~c in local rest frame) (Sari 1999)

Main Prediction:
P vanishes & reappears with $\theta_p$ rotated by 90°
Is not clearly observed

Also: $P \lesssim 10\%-20\%
While $P_{\text{obs}} \sim 1\%-3\%$
**Afterglow: Two “Traditional” Jet Structures**

**Uniform (top hat) jet:**
- No sideways expansion (Ghisellini & Lazzati 1999)
- Fast sideways expansion (∼c in local rest frame) (Sari 1999)

**Structured jet:**
- Postnov+01; Rossi+02; Zhang & Meszaros 02

**Log(\(dE/d\Omega\)) vs. Log(\(\theta\))

- \(\theta_0\)
- \(\theta_c\)

**Polarization light curve**
- Rossi et al. 2002

**Flux (mJy; R Band)**
Combining Ordered $B_{\text{ord}}$ & Random $B_{\text{rnd}}$ Fields

- $P_{\text{ord}} \sim P_{\text{max}} \sim 60\%$ & $\theta_p = 90^\circ$ w.r.t. the direction of $B_{\text{ord}}$

- In the afterglow $P \lesssim 3\% \Rightarrow I_{\text{ord}} \ll I_{\text{rnd}}$
  but we can still have $I_{\text{ord}} P_{\text{ord}} \geq I_{\text{rnd}} P_{\text{rnd}}$

- $\Rightarrow B_{\text{rnd}}$ dominates $I_{\text{total}}$
  but $B_{\text{ord}}$ dominates $IP$ & $P_{\text{total}}$

JG & Königl (2003)

\[ \eta = \eta(t) \]

\[ \eta = I_{\text{ord}} / I_{\text{rnd}} = \text{const} \]

\[ \beta = 0 \]
The Random B-field’s Degree of Anisotropy:

- \( b = 2\langle B_{\parallel}^2 \rangle / \langle B_{\text{perp}}^2 \rangle \) parameterizes the asymmetry of \( B_{\text{rnd}} \)
- \( \text{Sign}(b-1) \) determines \( \theta_p \) (\( P > 0 \) is along the direction from the line of sight to the jet axis & \( P < 0 \) is rotated by 90°)
- For \( b \approx 1 \) the polarization is very low (field is almost isotropic)
- \( P \leq 3\% \) in afterglows observations \( \Rightarrow 0.5 \leq b \leq 2 \)

\[ P = P_{\text{max}} /[1 + 2/(b-1)\sin^2 \theta'] \]

(valid for \( j' \nu \propto [B' \sin \chi']^2 \))

\[ \theta_0 = 5^\circ \]
\[ E_{\text{jet}} = 3 \times 10^{51} \text{ erg} \]
\[ n = 1 \text{ cm}^{-3} \]
\[ z = 1 \]
\[ p = 2.5 \]
\[ \varepsilon_e = 0.1 \]
\[ \varepsilon_B = 0.01 \]

\( (JG \ & \ Köngl \ 2003) \)
GW170817/GRB170817A Afterglow (Gill & JG 18)

- Assuming a shock-produce B-field with $b \equiv 2\langle B^2_\parallel \rangle / \langle B^2_\perp \rangle$
- Data favor two core-dominated jet models with similar $P(t)$

New: upper limit $P_{\text{lin}} < 12\%$ @ $\nu = 2.8\text{ GHz}$, $t = 244\text{ days}$ (Corsi + 2018)
More realistic assumptions ⇒ B-field in collisionless shocks:

- 2D emitting shell → 3D emitting volume (local BM76 radial profile)
- B-field evolution by faster radial expansion: \( \frac{L'_r}{L'_{\theta,\phi}} \propto \chi^{(7-2k)/(8-2k)} \)
- B-field isotropic in 3D with \( B'_r \rightarrow \xi B'_r \) (Sari 1999); \( \xi = \xi_0 \chi^{(7-2k)/(8-2k)} \)

\[
0.58 \leq \xi_f \leq 0.92
\]
Reverse shock Pol.: Ejecta B-field (Laskar + 2019)

- ALMA observed GRB190114C reverse shock at 97.5 GHz: $P \approx 0.9 \rightarrow 0.6\%, \Delta \theta_p \approx 54^\circ (2.2 \rightarrow 5.2 \text{ hr});$ 1st GRB radio pol.

- Low $P$: rules out $B_{\text{ord}}$ (with $\theta_B \geq 1/\Gamma$) for which $P \sim P_{\text{max}}$

- $B_{\text{ord}} + B_{\text{rnd}}$: $|I_{\text{ord}}|/|I_{\text{rnd}}| \sim 1$ & $I_{\text{ord}} \ll I_{\text{rnd}}$; FS ($t \ll t_j$), RS+FS

- $N \sim (\Gamma_{\text{ej}} \theta_B)^{-2}$ incoherent patches: $\Gamma_{\text{ej}} \approx 15$, $P \sim P_{\text{max}}/N^{1/2}$ ⇒ $\theta_B \sim P/P_{\text{max}} \Gamma_{\text{ej}} \sim 10^{-3}$ & $\Delta \theta_p \sim 1$ expected over $\Delta t \sim t$

- $\Delta \theta_p \approx 54^\circ$ rules out an axi-symmetric configuration (e.g. a global toroidal B-field in the original jet; A patchy shell?)
Prompt $\gamma$-ray Polarization: hard to measure

First consider synchrotron emission:

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

Waxman (2003)
Narrow Jet + shock produced B-field

- High polarization + reasonable flux \( \Rightarrow \theta_j < \theta_{\text{obs}} \leq \theta_j + 1/\Gamma \)
- A reasonable probability for such \( \theta_{\text{obs}} \Rightarrow \Gamma \theta_j \leq \) a few
- Since \( \Gamma \gtrsim 100 \) & \( \theta_j \gtrsim 0.05 \), \( \Gamma \theta_j \gtrsim 5 \) and is typically larger
- The jet must have sharp edges: \( \Delta \theta_j \leq 1/4 \Gamma \) (Nakar et al. 03)
- a ‘structured jet’ produces low polarization (several %)
- Most GRBs are viewed from \( \theta_{\text{obs}} < \theta_j \) and are expected to have a very low polarization in this scenario
- Afterglow obs. imply more random \( B_{\text{rnd}} \): \( 0.58 \lesssim \xi_f \lesssim 0.92 \)
Adding pulses: Random B-field in shock plane

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

\[ \mathcal{F}_\nu \propto \nu^{-\alpha} \]

- \( \Delta \Gamma \sim \Gamma \) between different shell collisions (different pulses in GRB light curve) reduces \( P \) by a factor \( \sim 2 \)

\[ \alpha = 1/2 \]
### Prompt $\gamma$-ray Polarization: short summary

<table>
<thead>
<tr>
<th></th>
<th>Ordered Field</th>
<th>Sharp-edge Jet</th>
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</thead>
<tbody>
<tr>
<td>$P \sim 80%$</td>
<td>$X$</td>
<td>$X$</td>
</tr>
<tr>
<td>$P \sim 50%$</td>
<td>$\checkmark$</td>
<td>$X$</td>
</tr>
<tr>
<td>$P \sim 25%$</td>
<td>with $B_{\text{rnd}} \leq B_{\text{ord}}$</td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>$P \leq 10%$</td>
<td>$B_{\text{rnd}} &gt; B_{\text{ord}}$</td>
<td>with $B_{\text{rnd}} \geq B_{\text{ord}}$</td>
</tr>
<tr>
<td>statistics</td>
<td>High $P$ in all GRBs</td>
<td>low $P$ in most GRBs</td>
</tr>
<tr>
<td>Potential problems</td>
<td>Some $B_{\text{rnd}}$ required for Fermi acceleration</td>
<td>$\Gamma \theta_j \lesssim a \text{ few}$, $\Delta \Gamma \sim \Gamma$, $B_{\text{rnd}}$ ($0.58 \lesssim \xi_f \lesssim 0.92$), $\Delta \theta_j \lesssim 1/4 \Gamma$</td>
</tr>
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Alternative to Synchrotron: Compton Drag
(Bulk Inverse Compton Scattering of External photons)

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

- Requires special geometry/viewing angle, $\theta_j < \theta_{\text{obs}} \leq \theta_j + 1/\Gamma$
- Polarization properties similar to synchrotron + $\mathbf{B}_{\text{rnd}}$ with an advantage: 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
Alternative to Synchrotron: Photospheric Emission

(Comptonized radiation advected from optically thick to thin region of the jet)

(Beloborodov 11; Thompson & Gill 14; Lundman+14; Vurm & Beloborodov 16; Lundman +16)

- Need to integrate radiation transfer equations for the Stokes parameters \( I(r,\mu) \) & \( Q(r,\mu) \) from \( \tau_T \gg 1 \) to \( \tau_T \ll 1 \).
- \( P=0 \) seed photons become anisotropic at \( \tau_T \leq 10 \implies P \approx 0.45 P_{\text{Compton-drag}} \)
- This requires symmetry breaking e.g.
  - special viewing angle: \( |\theta_{\text{obs}} - \theta_j| \lesssim 1/\Gamma \)
  - \( \theta \)-dependent bulk-\( \Gamma \) and/or luminosity (in structured jets \( P \leq 40\% \))

- Synchrotron + \( B_{\text{ord}} \) (spherical flow):
  Unscattered syn. photons emitted at \( \tau_T \sim 1 \) dominate at \( E \ll E_{pk} \implies P \sim P_{\text{syn, max}} \)

![Diagram showing Wien peak from thermal Comptonization and broadening](image)
Prompt GRB Polarization (Gill, JG & Kumar 2018):

- Comprehensive study in view of γ-ray polarimetry missions
- Jet structure: top hat (sharp/smooth), Gaussian, core+power-law
- Emission mechanism: synchrotron, photospheric, Compton drag
- Time resolved, integrated over single or multiple pulses

Random B-field in 2D  Order B-field  Toroidal B-field
Prompt GRB Polarization (Gill, JG & Kumar 2018):

- Model comparison: structured jet, integrating 10 pulses

Power Law Structured Jet: $a = b = 2$, $\alpha = 3/4$

$$\xi_c = (\Gamma_c \Theta_c)^2 \sqrt{\xi_{c,\text{min}}} = 10, \quad \sqrt{\xi_{c,\text{max}}} = 30$$

$$\frac{dE}{d\Omega} \propto \Theta^{-a}, \quad \Gamma_0 - 1 \propto \Theta^{-b}$$

$$\Theta = [1 + (\theta/\theta_c)^2]^{1/2}$$

- $B_{\perp}$
- $B_{\parallel}$
- $B_{\text{tor}}$
- CD

(99.9% C.L.)

(99% C.L.)

POLAR

IKAROS – GAP

AstroSat – CZTI

$B_{\text{tor}}/B_{\text{ord}}$ is favored if $P \sim 50$–65% in 1 ($\geq 20\%$ in most) GRBs
Conclusions:

- Afterglow polarization probes jet structure & dynamics + the B-field structure behind relativistic collisionless shocks

  $\Rightarrow$ GW170817: $0.58 < \xi_0 < 0.92 (B_{\text{rnd}}) + \text{core-dominated jet}$

- Reverse shock polarization probes B-field structure in ejecta

  - Optical flash ($\theta \sim 1/\Gamma_0 \lesssim 10^{-2}$), radio flare ($\theta \sim 1/\Gamma \sim 0.1$)
  - Reverse & forward (afterglow) shock emission may overlap

- GRB190114C: $B_{\text{ord}}$, axisymmetric $(B_{\text{tor}}, B_{\text{rnd}})$, $B_{\text{ord}} + B_{\text{rnd}} X$

  - patchy shell?, incoherent patches: $\theta_B \sim 10^{-3}$

- Prompt GRB pol. probes emission mechanism & jet structure

  - Observations are improving & new planned missions
  - Theory is improving to match the upcoming observations

  - $B_{\text{ord}}/B_{\text{tor}}$ favored if $P \sim 50-65\%$ in 1 ($\geq 20\%$ in most) GRBs