Polarization in Gamma-Ray Bursts

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

\( \sqrt{\xi_{\text{min}}} = 10, \sqrt{\xi_{\text{max}}} = 30 \)

Jet axis

Direction to the observer

Gamma-Ray Bursts & Related Astrophysics in Multi-Messenger Era

Nanjing, China, 13 May 2019
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 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 \( \mathbf{B} \) on the plane of the sky (normal to the wave vector)

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

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

\( n_{ph} = n_{sh} \)

Photon emitted normal to plane

Photon emitted along the plane

Magnetic field tangled within a (shock) plane
Relativistic Source:

Random field in shock plane

Sari 99; Ghisellini & Lazzati 99
Relativistic Source:

Random field in shock plane

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Sari 99; Ghisellini & Lazzati 99
Relativistic Source:

Random field in shock plane

Ordered field in shock plane

\[ P \sim P_{\text{max}} \]

Sari 99; Ghisellini & Lazzati 99

Granot & Königl 03
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)
Afterglow: Two “Traditional” Jet Structures

Uniform (top hat) jet:

(Rhoads 97,99; Sari+99, ...)

Log(\(dE/d\Omega\))

\(\theta_0\)

Log(\(\theta\))

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)

Structured jet:

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

Log(dE/dΩ) = θ

Log(θ)

Postnov+01; Rossi+02; Zhang & Meszaros 02

Log(dE/dΩ) = θ

Log(θ)

Rhoads 97,99; Sari+99, ...

Rossi et al. 2002

polarization light curve

degree of polarization (%)
Combining Ordered $B_{ord}$ & Random $B_{rnd}$ Fields

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

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

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

$\eta = \frac{I_{ord}}{I_{rnd}} = \text{const}$

$\eta = \eta(t)$

JG & Königl (2003)
The Random B-field’s Degree of Anisotropy:

- $b = 2 \frac{\langle B_{||}^2 \rangle}{\langle B_{\perp}^2 \rangle}$ 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 $90^\circ$)
- 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 $j' \propto \langle B' \sin \chi' \rangle^2$)

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

(JG & Königl 2003) $t$ [days]
- 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 $P(t)$
GW170817/GRB170817A Afterglow (Gill & JG 18)

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New: upper limit $P_{\text{lin}} < 12\%$ @ $\nu = 2.8$ GHz, $t = 244$ days (Corsi + 2018)
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\[
\theta_{\text{min}}(t) = \theta_c
\]

\[
b = 0 \quad b = 0.7 \quad b = 0.5 \quad b = 1.5
\]

\[
P_{\text{lin}} < 12\% \quad @ \quad v = 2.8 \text{ GHz}, \quad t = 244 \text{ days} \quad (\text{Corsi} + 2018)
\]
More realistic assumptions ⇒ B-field in collisionless shocks:
- 2D emitting shell → 3D emitting volume (local BM76 radial profile)
GW170817/GRB170817A Afterglow (Gill & JG19)

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- 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); \( \xi = \xi_0 \chi^{(7-2k)/(8-2k)} \)

\[ \begin{align*}
\xi &= 1.3 \\
\xi &= 1 \\
\xi &= 0.8 \\
\xi &= 0.65 \\
\xi &= 0.5 \\
\xi &= 0.3
\end{align*} \]
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| \( \Pi \) | < 12% at \( \approx 244 \) days

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\[ 0.48 < \xi_0 < 0.79 \]

\[ |\Pi| < 12\% \text{ at } \approx 244 \text{ days} \]
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 → 5.2 hr); 1st GRB radio pol.
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- Low P: rules out B_{ord} (with θ_B ≥ 1/Γ) for which P ~ P_{max}
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- Low \( P \): rules out \( B_{\text{ord}} \) (with \( \theta_B \geq 1/\Gamma \)) for which \( P \sim P_{\text{max}} \)

- \( B_{\text{ord}} + B_{\text{rnd}} \): \( \mathbb{P}|_{\text{rnd}}/\mathbb{P}|_{\text{ord}} \sim 1 \) & \( I_{\text{ord}} \ll I_{\text{rnd}} \); \( FS \) (\( t \ll t_j \)), \( RS+FS \)
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- \( N \sim (\Gamma_{\text{ej}} \theta_B)^{-2} \) incoherent patches: \( \Gamma_{\text{ej}} \approx 15 \), \( P \sim P_{\text{max}} / N^{1/2} \) \( \Rightarrow \)

\[
\theta_B \sim P / P_{\text{max}} \Gamma_{\text{ej}} \sim 10^{-3} \) \& \( \Delta \theta_p \sim 1 \) expected over \( \Delta t \sim t \)

\[
\text{Flux density (mJy)} \quad \text{Probability density} \quad \text{Time since burst (hours)}
\]
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- $B_{ord} + B_{rnd}$: $|I|_{rnd}/|I|_{ord} \sim 1$ & $I_{ord} \ll I_{rnd}$; $FS (t \ll t_j)$, $RS + FS$

- $N \sim (\Gamma_{ej} \theta_B)^{-2}$ incoherent patches: $\Gamma_{ej} \approx 15$, $P \sim P_{\text{max}}/N^{1/2} \Rightarrow \theta_B \sim P/P_{\text{max}} \Gamma_{ej} \sim 10^{-3}$ & $\Delta \theta_p \sim 1$ 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 $\theta_{\text{obs}} \Rightarrow \Gamma \theta_j \leq \text{a few}$
- Since $\Gamma \geq 100$ & $\theta_j \geq 0.05$, $\Gamma \theta_j \geq 5$ and is typically larger
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- The jet must have sharp edges: $\Delta \theta_j \lesssim 1/4\Gamma$ (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
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- Afterglow obs. imply more random $B_{\text{rnd}}$: $0.48 < \xi_0 < 0.79$
Adding pulses: Random B-field in shock plane

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

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

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

\( \alpha = 1/2 \)

(Granot 2003)
Prompt $\gamma$-ray Polarization: short summary

<table>
<thead>
<tr>
<th></th>
<th>Ordered Field</th>
<th>Sharp-edge 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>$B_{\text{rnd}} \leq B_{\text{ord}}$</td>
<td>✓</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>$\Gamma \theta_j \leq \text{a few, } \Delta \Gamma \sim \Gamma$, $B_{\text{rnd}} (0.48 &lt; \xi_0 &lt; 0.79)$</td>
</tr>
</tbody>
</table>
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, \(\theta_j < \theta_{obs} \leq \theta_j + 1/\Gamma\)
- Polarization properties similar to synchrotron + \(B_{\text{rnd}}\) 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
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- Polarization properties similar to synchrotron + $B_{\text{rnd}}$ 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
- It has additional problems, unrelated to polarization:
  - Explaining prompt GRB spectrum
  - Supplying external photons for all the ejected shells
  - High photon density $\Rightarrow$ small radii $\Rightarrow$ high $\tau_{\gamma\gamma}$

![Diagram showing scattering volume and components of electron and electric field movements.](image)
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 $\tau_T \leq 10 \Rightarrow P \approx 0.45P_{\text{Compton-drag}}$
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- This requires symmetry breaking e.g.
  - special viewing angle: $|\theta_{\text{obs}} - \theta_j| \leq 1/\Gamma$
  - $\theta$-dependent bulk-$\Gamma$ and/or luminosity (in structured jets $P \leq 40%$)
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- Need to integrate radiation transfer equations for the Stokes parameters $I(r,\mu) & Q(r,\mu)$ from $\tau_T > 1$ to $\tau_T < 1$.
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  - 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 $E \ll E_{\text{pk}} \Rightarrow P \sim P_{\text{syn,max}}$

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**GRB 09092B**
(Lundman + 2016)

- Wien peak from thermal Comptonization of soft synchro. photons at $\tau_T > 10$
- Wien peak broadened into non-thermal spectrum by unsaturated Comptonization at $\tau_T < 10$; Also yields $\alpha \sim -1$

- Synchrotron emission in a uniform B-field from non-thermal $e^-$

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**Fermi GBM window**
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  Ordered B-field  Toroidal B-field
Prompt GRB Polarization (Gill, JG & Kumar 2018):

- Model comparison: **structured jet, integrating 10 pulses**

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

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

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

\( \mathbf{B_{tor}}/\mathbf{B_{ord}} \) is favored if \( P \sim 50-65\% \) in 1 (\( \gtrsim 20\% \) in most) GRBs
Conclusions:

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

$\Rightarrow$ GW170817: $0.48 < \xi_0 < 0.79$ ($B_{\text{rnd}}$) + core-dominated jet
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- **Afterglow polarization** probes jet structure & dynamics + the B-field structure behind relativistic collisionless shocks
  - $0.48 < \xi_0 < 0.79$ ($B_{\text{rnd}}$) + 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 ($B_{\text{tor}}, B_{\text{rnd}}$), $B_{\text{ord}} + B_{\text{rnd}} \times$ patchy shell?, incoherent patches: $\theta_B \sim 10^{-3}$ ✓
Conclusions:

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

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