GRB Afterglow Polarization & GRB170817A

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Shedding New Light on Gamma-Ray Bursts with Polarization Data
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Outline of the Talk:

- Polarization of synchrotron rad. from a relativistic source
- Afterglow: Jet structure & dynamics, B-field structure
  - Top hat vs. structured jet
  - Shock-produced vs. ordered B-field
- Reverse shock emission: optical flash & radio flare
- GRB170817A / GW170817 – the afterglow emission:
  - Two main options for the early flux rise: $r$ vs. $\theta$ dependence
  - Breaking the degeneracy: lightcurves? Images, Polarization
  - New observations imply: dominant $\theta$ dependence (off-axis jet)
- Conclusions
Polarization of Synchrotron Emission

- **Linear polarization** 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 \( F_\nu \propto \nu^{-\alpha} \), \(-1/3 \leq \alpha \leq 1.5 \) \( \Rightarrow 50\% \leq P_{\text{max}} \leq 80\% \) (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)
Pure shock-produced magnetic field:

- Symmetric w.r.t. the normal to the shock, \( \mathbf{n}_{sh} \)
- Produces no net polarization for a spherical outflow
- Breaking the circular symmetry of the observed image:
  - jet viewed from \( \theta_{\text{obs}} > 0 \) (Sari 99; Ghisellini & Lazzati 99)
  - Scintilations (relevant for radio) (Medvedev & Loeb 1999)
  - Microlensing (rare event) (Loeb & Perna 1998)
  - Clumps, patchy shell (LC variability) (JG & Königl 2003)
- The polarization light curves for a jet depend on:
  - The jet structure: uniform (Sari 99; Ghisellini & Lazzati 99) or smoothly varying with angle from its axis (Rossi et al. 03)
  - The jet dynamics (degree of lateral spreading, etc.)
  - The magnetic field structure in the emitting region
Effect of B-field degree of anisotropy:

- There are a wide variety of possible B-field configurations in the emitting region that affect the local polarization (Sari 1999).

\[
\Pi_p = \Pi_0 \frac{\int \cos 2\eta[B(\theta) \sin \delta] f(\theta) \sin \theta d\phi d\theta}{\int [B(\theta) \sin \delta] f(\theta) \sin \theta d\phi d\theta}.
\]

For a power-law distribution of electrons, we have \( \Pi_0 = (p + 1)/(p + 7/3) \) and \( \epsilon = (p + 1)/2 \), where \( p \) is the electron power-law index, usually in the range of \( p = 2 \) to \( p = 2.5 \). Reasonable values are therefore \( \Pi_0 \sim 70\% \) and \( 1.5 < \epsilon < 1.75 \). Cooling may increase the effective \( p \) by 1/2.

For frequency integrated polarization, the emission is proportional to the square of the magnetic field, \( \epsilon = 2 \), and the integration can be easily done. We obtain

\[
\Pi_p = \Pi_0 \frac{\langle B_\parallel^2 \rangle - \langle B_\perp^2 \rangle / 2}{\sin^2 \alpha \langle B_\parallel^2 \rangle + (1 + \cos^2 \alpha) \langle B_\perp^2 \rangle / 2}.
\]

This is identical to the expression of Gruzinov (1999). As we remarked above, the relevant values of \( \epsilon \) are probably below 2, and the integration is less simple. The results now depend on higher moments of \( B(\theta) \) and \( f(\theta) \), rather than simply through \( \langle B_\parallel^2 \rangle \) and \( \langle B_\perp^2 \rangle \). One realization of anisotropic magnetic field can be obtained from an isotropic magnetic field in which the component in the parallel direction was multiplied by some factor \( \xi \). In the notation above this translates to

\[
B(\theta) \propto (\xi^2 \sin^2 \theta + \cos^2 \theta)^{-1/2}, \quad f(\theta) \propto B^3(\theta).
\]
Relativistic source:

Aberration of light or ‘relativistic beaming’

The observer sees mostly emission from within an angle of $1/\Gamma$ around the l.o.s.

Direction of Polarization

Direction to observer
Polarization in the observer frame

Random field in shock plane

Ordered field in shock plane

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

Sari 99; Ghisellini & Lazzati 99

Granot & Königl 03
Two Competing Jet Structures:

**Uniform (top hat) jet**:  
\[ \log(\theta) \]

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

- A structured jet has a \( \sim 10 \) times larger energy than a uniform jet, and implies a \( \sim 10 \) times smaller GRB rate.
- The jet structure constrains model for the central source.
- There are small differences in the light curves of the two jet structures (Granot & Kumar 2003; Kumar & Granot 2003).
- Structured jet predicts \( \frac{dn}{dzd\theta} \) (Nakar, Granot & Guetta 2004).

† Rhoads 97,99; Sari et al. 99, ...

†† Postnov et al. 01; Rossi et al. 02; Zhang & Meszaros 02
Polarization light curves: Uniform jet

1. No sideways Expansion (Ghisellini & Lazzati 99)
2. Very fast sideways Expansion (~c in local rest frame) (Sari 1999)

\[ \frac{\theta_o}{\theta_e} = 0.087 \]

\[ \frac{\theta_o}{\theta_e} = 0.1 \]
\[ \frac{\theta_o}{\theta_e} = 0.4 \]
\[ \frac{\theta_o}{\theta_e} = 0.67 \]
\[ \frac{\theta_o}{\theta_e} = 0.9 \]

\[ q = 0.95 \]
\[ q = 0.71 \]
\[ q = 0.32 \]
**Polarization light curves: Uniform jet**

No sideways Expansion  
(Ghisellini & Lazzati 99)

Very fast sideways Expansion  
(\(\sim c\) in local rest frame)  
(Sari 1999)

Main Prediction: \(\theta_p\) rotates by 90° as \(P\) passes through zero

Was never observed

Also: \(P \leq 10\%-20\%\)

\[\theta_\alpha / \theta_\pi = \{0.1, 0.4, 0.67, 0.9\}\]

\[\gamma^{-1} = 0.087\]
Polarization light curves: Structured jet

- P peaks at jet break time, $\theta_p = \text{const}$, $P \lesssim 10\% - 30\%$

(Rossi et al. 2002)
Observations: Afterglow Polarization

- 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.

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(Gorosabel et al. 1999)
Effect of Magnetic field structure:

- $b = 2\langle B_\parallel^2 \rangle / \langle B_{\text{perp}}^2 \rangle$ 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 $90^\circ$)

- For $b \approx 1$ the polarization is very low (field is almost isotropic)

- $P \lesssim 3\%$ in afterglows observations $\Rightarrow 0.5 \lesssim b \lesssim 2$

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

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

Motivation: amplification of ambient B-field

- At shock transition: $B_\parallel$ remains unchanged, $B_{\perp}$ is amplified by the compression ratio ($4\Gamma$ for $\Gamma \gg 1$) $\Rightarrow$ we expect $B_{\perp} \gg B_\parallel$ and for simplicity assume $B_\parallel = 0$

- Afterglow observations $\Rightarrow$ $10^{-4} \leq \varepsilon_B \leq 0.1$, $P \leq 0.05P_{\text{max}} \Rightarrow 10^{-5.5} \leq \varepsilon_{B,\text{ord}} \leq 10^{-2.5}$

- Values expected for the external medium:
  - Pulsar wind bubble (Königl & Granot 02): $\varepsilon_{B,\text{ord}} \sim 10^{-3} - 10^{-1}$
  - Stellar wind of massive star progenitor: $\varepsilon_{B,\text{ord}} \sim 10^{-6} - 10^{-4}$
  - Interstellar medium (ISM): $\varepsilon_{B,\text{ord}} \sim 10^{-10} - 10^{-8}$, however if the magnetic field is amplified in the shock preferentially in the direction of the initial field, then $\varepsilon_{B,\text{ord}}$ can be high enough
Combining $B_{\text{ord}}$ & $B_{\text{rnd}}$:

- $P_{\text{ord}} \sim P_{\text{max}} \sim 60\%$ & $\theta_p = 90^\circ$ w.r.t. the direction of $B_{\text{ord}}$
- In the afterglow we must have $I_{\text{ord}} \ll I_{\text{rnd}}$ so that $P \lesssim 3\%$
- but we can still have $I_{\text{ord}}P_{\text{ord}} \gtrsim I_{\text{rnd}}P_{\text{rnd}}$
- $\Rightarrow B_{\text{rnd}}$ dominates $I_{\text{total}}$ but $B_{\text{ord}}$ dominates $IP$ & $P_{\text{total}}$

Granot & Königl (2003)
Adding evolution of $I_{\text{ord}}/I_{\text{rnd}}$ with radius:
can explain $\theta_p \approx \text{const} & \text{variable } P$
Predictions for an ordered B-field:

- $P(t \ll t_j) \sim P(t \sim t_j)$ while for jet+$B_{\text{rnd}}$ models: $P(t \ll t_j) \ll P(t \sim t_j)$

- Emission from the original ejecta (prompt GRB & reverse shock) may have $P \sim P_{\text{max}} (\leq 60\%)$ due to an ordered B-field carried by the ejecta from the source.

- If $B_{\text{ord}}$ in the ejecta is ordered on angles $1/\Gamma_0 \leq \theta_B \leq 0.1$ then $P \sim P_{\text{max}} \times \min(1, \Gamma \theta_B)$ due to averaging over $N \sim (\Gamma \theta_B)^{-2}$ incoherent patches.

- $\Rightarrow P$ can be smaller & $\theta_p$ different in the ‘radio flare’ ($\Gamma \sim 10$) compared to the ‘optical flash’ ($\Gamma \sim \Gamma_0 \sim 300$).
Reverse shock Pol.: B-field in ejecta

- The existence of a reverse shock $\Rightarrow E_{EM} \lesssim E_{kin} \ (\sigma \lesssim 1)$
- In the ‘optical flash’ the pol. should be similar to that in $\gamma$-rays, but much easier to measure & more reliable
- If $B_{ord}$ in the ejecta is ordered on angles $1/\Gamma_0 \lesssim \theta_B < \theta_j$ then $P \approx P_{max} \times \min(1, \Gamma\theta_B)$ due to averaging over $N \sim (\Gamma\theta_B)^{-2}$ incoherent patches (Granot & Königl 03) $\Rightarrow$ smaller $P$ & different $\theta_p$ in the ‘radio flare’ ($\Gamma \sim 10$)
- Toroidal B-field in the ejecta:

\[ q = \frac{\theta_{obs}}{\theta_0} = 0.9 \]

structured jet

(Lazzati et al. 2004)
<table>
<thead>
<tr>
<th>B-field</th>
<th>Optical Flash</th>
<th>Radio Flare ((t \sim t_j))</th>
</tr>
</thead>
</table>
| Shock Produced       | \(\theta_{\text{obs}} \lesssim \theta_j - 1/\Gamma: P \approx 0\)  
                        \(\theta_{\text{obs}} \sim \theta_j + 1/\Gamma: P \leq 50\%\)  
                        \(\text{pol. due to jet structure}\)  
                        \(\Rightarrow\) similar to afterglow |
| Uniform              | \(P \sim P_{\text{max}}\)  
                        \(P \sim P_{\text{max}}\) |
| Patches \((\theta_B)\) | \(\theta_B \gtrsim 1/\Gamma_0: P \sim P_{\text{max}}\)  
                        \(P \sim P_{\text{max}} \times \min(1, \Gamma \theta_B)\) |
| Toroidal             | \(1/\Gamma_0 \lesssim \theta_{\text{obs}} \lesssim \theta_j:\)  
                        \(P \sim P_{\text{max}}\)  
                        \(\text{structured jet: } P \sim P_{\text{max}}\)  
                        \(\text{tophat: } P \sim P_{\text{max}} (\theta_{\text{obs}}/\theta_j)^2\) |
Upper Limits on Polarization of Radio Flare Emission (Granot & Taylor 2005)

<table>
<thead>
<tr>
<th>GRB</th>
<th>t (days)</th>
<th>t_j (days)</th>
<th>Π_L (3 σ)</th>
<th>Π_C (3 σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>990123</td>
<td>1.25</td>
<td>≈ 2</td>
<td>&lt; 23%</td>
<td>&lt; 32%</td>
</tr>
<tr>
<td></td>
<td>1.49</td>
<td>2.68</td>
<td>&lt; 11%</td>
<td>&lt; 17%</td>
</tr>
<tr>
<td>991216</td>
<td>2.68</td>
<td>1.49, 2.68</td>
<td>&lt; 9%</td>
<td>&lt; 15%</td>
</tr>
<tr>
<td></td>
<td>1.49</td>
<td></td>
<td>&lt; 7%</td>
<td>&lt; 9%</td>
</tr>
<tr>
<td>020405</td>
<td>1.19</td>
<td>≈ 1-2</td>
<td>&lt; 11%</td>
<td>&lt; 19%</td>
</tr>
</tbody>
</table>

- Probably almost no depolarization in the host galaxy
- Likely no significant depolarization in the source due to different amounts of Faraday rotation; hard to rule out
Toroidal Magnetic Field:

**Dynamics of the Ejecta:**

\[ \Gamma(t) \text{ follows that of the forward shock} \]

\[ \Gamma(t) \text{ follows the Blandford \\& McKee self similar solution} \]

\[ \Gamma(t) \text{ follows that of the forward shock} \]
# Implications of the Upper limits on the Radio Flare Polarization

<table>
<thead>
<tr>
<th>B-field structure</th>
<th>Theoretical prediction</th>
<th>Theory vs. Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shock Produced</td>
<td>pol. due to jet structure ⇒ similar to afterglow</td>
<td>✓</td>
</tr>
<tr>
<td>Uniform</td>
<td>$P \sim P_{\text{max}}$</td>
<td>$X$</td>
</tr>
<tr>
<td>Patches ($\theta_B$)</td>
<td>$P \sim P_{\text{max}} \times \min(1, \Gamma \theta_B)$</td>
<td>$\theta_B \leq P_{\text{lim}}/\Gamma P_{\text{max}} \sim 10^{-2}$</td>
</tr>
<tr>
<td>Toroidal</td>
<td>structured jet: $P \sim P_{\text{max}}$ tophat: $P \sim P_{\text{max}} (\theta_{\text{obs}}/\theta_j)^2$</td>
<td>$X$</td>
</tr>
</tbody>
</table>
GRB 170817A: afterglow observations

$F_v \propto \nu^{-0.61} t^{0.78\pm0.05}$ (Mooley et al. 2018)
GRB 170817A: afterglow observations

\[ F_v \propto v^{-0.61} t^{0.78 \pm 0.05} \]

A rise lasting > 100 days is very unusual!!

(Mooley et al. 2018)
Analogy to rising $F_v$: X-ray Plateaus

**Possible solutions:**

- Evolution of shock microphysical parameters (JG, Konigl & Piran 2006)
- Energy injection into ext. shock:
  1. long-lived relativistic wind
  2. slower ejecta catching up (Sari & Meszaros 00; Nousek 06; JG & Kumar 06)

**Viewing angle effects**

Energy injection into the afterglow shock:

$1 \leq a \leq 2.5$ (ISM)

$a \geq 5$ (wind)

(Vaughan et al. 2006)

(JG & Kumar 2006)
Analogy to rising $F_v$: X-ray Plateaus

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- Energy injection into the afterglow shock
  
  $1 \leq a \leq 2.5$ (ISM)
  
  $a \geq 5$ (wind)

- Viewing angle effects
The emission is initially strongly beamed away from our L.o.S.

- $F_v$ rises as beaming cone widens.
- When beaming cone reaches LoS, $F_v$ peaks & approaches on-axis $F_v$.
- The rise is much more gradual for hydrodynamic simulations due to slower matter at the jet’s sides with non-radial velocities.
GRB170817 outflow structure: prompt, afterglow

- Cocoon model (Kasliwal+17; Mooley+18; Nakar & Piran 18): $r \& \theta$ profile
- Cocoon-driven shock breakout can naturally produce the $\gamma$-rays (Kasliwal+17; Gottlieb+17; Bromberg+18; Nakar & Piran 18; Nakar+18)
GRB170817 outflow structure: the afterglow

- **A structured jet explanation** (Lazzati+17; Margutti+18; Gill & JG 18;...):
  - Simulation of jet breaking out of the Newtonian ejecta near a NS-NS merger site: the **cocoon** energizes the jet’s sides/wings
  - Afterglow dominated by $\theta$ profile

(Lazzati et al. 2018)
Outflow structure: breaking the degeneracy (Gill & JG 18)

- The lightcurves leave a lot of degeneracy between models
- The degeneracy may be lifted by calculation the afterglow images & polarization (e.g. Nakar & Piran 2018; Nakar et al. 2018)
- We considered 4 different models including both main types
  - **Sph+E\(_{\text{inj}}\):** Spherical with energy injection \(E(\geq u > \Gamma \beta) \propto u^{-6}, \ 1.5 < u < 4\)
  - **QSph+E\(_{\text{inj}}\):** Quasi-Spherical + energy injection \(E(\geq u) \propto u^{-s}, u_{\text{min},0} = 1.8, u_{\text{max},0} = 4, s = 5.5, \zeta = 0.1\)

\[
\frac{e(\theta)}{e(0)} = \frac{u_{\text{min}}(\theta)}{u_{\text{min},0}} = \frac{u_{\text{max}}(\theta)}{u_{\text{max},0}} = \frac{\zeta + \cos^2 \theta}{\zeta + 1}
\]
Outflow structure: breaking the degeneracy (Gill & JG 18)

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- We considered 4 different models including both main types
  - GJ: Gaussian Jet (in $\varepsilon = dE/d\Omega$, $\Gamma_0 - 1$) $\Gamma_c = 600$, $\theta_c = 4.7^\circ$
  - PLJ: Power-Law Jet; $\varepsilon = \varepsilon_c \Theta^{-a}$, $\Gamma_0 - 1 = (\Gamma_c - 1)\Theta^{-b}$, $\Theta = [1+(\theta/\theta_c)^2]^{1/2}$ $\Gamma_c = 100$, $\theta_c = 5^\circ$, $a=4.5$, $b=2.5$
- As there is a lot of freedom we fixed: $p=2.16$, $\varepsilon_B = n_0 = 10^{-3}$, $\theta_{\text{obs}} = 27^\circ$
The outflow structure: breaking the degeneracy

- Tentative fit to GRB170817A afterglow data (radio to X-ray)
The outflow structure: breaking the degeneracy

- Tentative fit to GRB170817A afterglow data (radio to X-ray)
The outflow structure: breaking the degeneracy

- New data that came out established a peak at $t_p \sim 150$ days
- The jet models decay faster (slightly preferred by the latest data)

Decay: $\sim t^{-2.2}$
(Mooley+18)
Afterglow Images: Sph + E_{inj}
Afterglow Images: \( QSph + E_{\text{inj}} \)

Jet symmetry axis

\( \theta_{\text{obs}} \)

Direction to observer

\( \tilde{y}, y \)

\( \tilde{x} \)

\( x \)

\( z \)

Log\(_{10}(I_\nu/\langle I_\nu \rangle)\)
Afterglow Images: GJ, PLJ
Linear Polarization

- Assuming a shock-produce B-field with $b \equiv 2\langle B^2 \parallel \rangle / \langle B^2 \perp \rangle$
Linear Polarization

- Assuming a shock-produce B-field with $b \equiv 2\langle B_{||}^2 \rangle / \langle B_{\perp}^2 \rangle$

![Graph showing linear polarization versus time with different curves for $b = 0$, $b = 0.7$, $b = 0.5$, and $b = 1.5$. The graph illustrates how the minimum polarization angle, $\theta_{\text{min}}(t)$, changes with different values of $b$.]

- New: upper limit on linear pol. @ 2.8 GHz (Corsi + 2018)

- $0.7 \leq b \leq 1.5$ for jet models
Afterglow Images: **flux centroid, size, shape**

- The flux centroid motion: a potentially powerful diagnostic
- It may be hard to tell apart models based on the image size alone, but a much higher axis-ratio is expected for jet models.
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(Mooley et al. 2018)

\[ \pm \]

(Ghirlanda et al. 2018)
Afterglow Images: uniform jet simulations

(JG, De Colle & Remirez-Ruiz 2018)
Conclusions:

- **Afterglow polarization** probes jet structure & dynamics + the B-field structure behind relativistic collisionless shocks.
- 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.
- More afterglow polarization **observations are needed!!!**
- GW170817 afterglow: main explanations for the rising flux energy distribution with proper velocity ($r$) or with angle ($\theta$).
- Diagnostics: post-peak flux decay slope, image axis ratio, flux centroid motion (image size or polarization alone: hard).
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- New flux centroid motion observations: $\beta_{\text{app}} = 4.1 \pm 0.5$
- $0.7 \lesssim b \lesssim 1.5$ in the afterglow shock ($b = 2\langle B_\parallel^2 \rangle / \langle B_{\text{perp}}^2 \rangle$).