Implications of polarization in GRBs and parsec-scale AGN jets

Maxim Lyutikov (McGill, CITA)

in collaboration with

V. Pariev (Rochester)
D. Gabuzda (Cork U.)
R. Blandford (Stanford),
Composition of ultra-relativistic jets

- Pulsars, \( \sim 10^6 \)
- AGNs, \( \sim 10^{-30} \)
- GRBs, \( \sim 100-1000 \)
- Microquasars, \( \sim 2 \)
- X-ray binaries, \( \sim 10 \)

All outflows are collimated

What carries the bulk of the energy?

- Ions (most people think)
- pairs
- B-field (In emission region \( \sim \) equipartition
  (amplify B-field or dissipate B-field); Polarization)
This talk

- Observational evidence of large scale B-fields:
  - AGN pc-scale jets
  - GRBs
- Electromagnetic model of GRBs
Large scale B-fields in AGNs (pc scale)

- Jets are launched and collimated electromagnetically (Lovelace et al., Blandford & Znajek, Blandford & Payne, Camenzind, Fendt; Koide, Shibata and others).
- Is \( \text{ } \) at pc scale consistent with large scale B-field? (in radio: synchrotron)
Synchrotron emission by relativistic sources

- In plasma frame
- In laboratory frame

\[ \Pi_{\text{max}} = \frac{p + 1}{p + 7/3} \]

Both B-field and velocity field are important for:

\[ \vec{e} = \frac{\vec{n} \times \vec{q}}{\sqrt{q^2 - (\vec{n} \cdot \vec{q})^2}} \]

\[ \vec{q} = \vec{B} + \vec{n} \times (\vec{v} \times \vec{B}) \]

\[ (\vec{e} \cdot \vec{B}) = (\vec{e} \times \vec{n})(\vec{B} \times \vec{v}) \neq 0 \]
from relativistic helical jet

Relativistic jet, \(_ \gg 1\), carrying helical B-field

\[
\tan \psi = \frac{B_{\psi}}{B_z}
\]

\(_ = 2, \_ = \pi/4, \_ob = \pi/3\)

- B not orthogonal to e
- e “above” and “below” are different (handedness of a jet)

(Observers: always plot direction of polarization, not “inferred” B-field)
from cylindrical shell

- depends on $p$
- Even co-spatial populations with different $p$ may give different _
  (eg Radio & Optical)

$\tan \psi = \frac{B_q}{B_z}$

$= 10, \ p = 1, \ different \ pitch \ angles$
Large scale B-field in AGNs

- Bimodal distribution of PA
  - (Aller et al)

- PA follows the jet as it bends
  - (Gabuzda 03)

- Sometimes a bend gives a 90° change of PA

- For cylindrical jet $U=0$, average $\_\_$ along or across the axis

- For fixed $\_\_$, $\_\_$ mostly keeps its sign

- Sometimes a change does occur
Resolved jets

- Resolved jets: center: PA along, edges: PA across

Jet internal structure: Force-free jet

- $B'_\phi = \frac{r/r_0}{1+(r/r_0)^2} B'_0$
- $B'_{\phi} = \frac{1}{1+(r/r_0)^2} B'_0$

- $B'_\phi = 0$ on the axis: PA across the jet
- Finite $B'_\phi \geq B'_z$: PA along the jet
- On the edge $B'_\phi = 0$, PA across
- How emissivity $\phi$ scales with $B$?

(Gabuzda 03)
Jet polarization may tell the spin of BH

- Left & Right helixes look different
- Different signature
- May tell direction of BH or disk spin
Gradient of Rotation
Measure across the jet

Helical field
$RM \sim \int B_{ndl} - \text{sign-dependent}$

(Gabuzda 03)
AGNs

- In a relativistic jet, \( \gg 1 \), in order to have PA along the jet, it is needed \( \frac{B'}{B'_{\parallel}} \geq 1 \) \( \frac{B}{B_{\parallel}} \sim \gg 1 \)
- BL Lac jet are strongly dominated by \( B_{\perp} \) (expected due to expansion)
- Large scale B-fields may explain polarization of pc-scale AGN jets (Lyutikov, Pariev, Gabuzda 04)

Polarization in X-ray jets: emission mechanism
- Synchrotron (and SSC): _ across or along the jet
- IC on external photons: _ across the jet
in GRBs: prompt emission

- Coburn & Boggs: limited by systematic errors (mass model of the spacecraft)
- Rutledge & Fox: statistical error (number of counts)
- Big difference is how many are there “good” double counts
- CB: ~ 10000, RF ~ 800
- RF: there are too few double counts to place any constraint on _
- Both groups stand by their results
- Results (negative) from RHESSI people are expected.

If confirmed, what are the implications of _?
Polarization from expanding sources

- Both B-field and velocity field are important for \( B \sim c \)

(Lyutikov, Pariev, Blandford 03)
Different GRB models

EM & MHD

Internal shocks

Cannonballs

\[ \Delta \theta \sim 1 \gg 1/\Gamma \]
\[ \theta_{ob} \sim \text{any} \]
\[ \Pi_{\text{max}} \sim 50\% \]
\[ \text{Probability} \sim 1 \]

\[ \Delta \theta \sim 1/\Gamma \]
\[ \theta_{ob} \sim 1/\Gamma \]
\[ \Pi_{\text{max}} \sim 35\% \]
\[ \text{Probability} \sim 10^{-4} \]
\[ \text{All } \Gamma \sim \text{same} \]
\[ \text{B-field must be 2D} \]

\[ \Delta \theta \sim 10^{-3} \ll 1/\Gamma \]
\[ \theta_{ob} \sim 1/\Gamma \]
\[ \Pi_{\text{max}} \sim 100\% \]
\[ \text{Probability} \sim 10^{-4} \]

\[ \Delta \theta \]
\[ \theta_{ob} \]

Synchrotron
_in the plane O-A

In the plane O-A
Polarization in prompt GBR emission

- **GRB prompt polarization:**
  - If \( \geq 60\% \) only IC
  - \( 10\% \leq \_ \leq 60\% \) Synchrotron or SSC from large scale B-fields
  - \( \_ \leq 10\% \) synchrotron from small scale B-field
  - Need long bright burst
Electromagnetic model of GRB (Lyutikov & Blandford 2003)
Ultra-relativistic jets

**Conventional view** (e.g. internal shocks model):

- **B-field is important at the source:**
  - B-field extracts energy from the BH/progenitor
  - Dissipates it right away into \(-e^\pm\) or e-i plasma
  - Energy goes in bulk, reconvert into internal at shocks
  - Regenerate B at shocks, produce \(-X-O\) emission

**Direct route:**

- **Extract energy in B-field, propagate, dissipate**
  - B-field is naturally relativistic (if not tied-up or contaminated)
  - Self-collimating
Implication of prompt GRB polarization

Magnetization parameter

\[ \sim \frac{B^2}{4 \pi \epsilon^2} = \frac{F_P}{F_M} (B - \text{ordered field}) \]

Fireballs model is excluded

\[ \sim 0 \]

\[ \sim 1 \]

\[ \infty \]

Fireballs (internal shocks):
hydrodynamics, small scale B-field

MHD

Thompson; Spruit et al.; Vlahakis & Konigl;

Uslov; Oueder & Fendt; Lyutikov & Blackman

Force-free, \( \_ > _2 \)

Lyutikov & Blandford
in EM model

- **Prompt emission:**
  - Causally-connected outflow: natural to have large scale B-fields
  - _ should correlate with _, _ ≤ 60%
  - PA should not change
- PA in prompt and afterglow may correlate
**Polarization in afterglow**

- B-field from ejecta can be mixed with ISM
  - Magnetic Richtmeier-Meshkov instability (Lyutikov & Blandford03)
  - braiding of field-lines
- No 90° change of PA (unlike uniform jet model): change never observed
- No relation to jet break (unlike structured jets with random B-field) – confirmed (?)
- constant PA (same for prompt and afterglow)

changes of PA are seen only in strongly variable sources
Implications of EM model

- **B-field dissipation due to current instabilities** — (“reconnection-type” $E_B - E_{\text{plasma}}$, c.f. Solar flares)

- Investigations of strongly magnetized plasmas are only beginning
  - $_e = \infty$. Tearing mode in RFF (unsteady reconnection) (Lyutikov 2003)
  - $_e \gg 1$. Steady-state relativistic reconnection (Lyutikov & Uzdensky 2002)
  - Simulations (Larrabee et al.; Zenitani & Hoshino; Liang et al.)

- Distinguishable by spectra (may be very hard, $dn/d_\sim \sim -1$)
- Shock acceleration works for $_e \geq m_p/m_e \geq 2000$

- Large scale B-field: PA may fluctuate, but not by much
Conclusion

- Large scale magnetic fields are dynamically important and may be dominant in ultra-relativistic outflows
- Synchrotron (and possibly SSC) from large scale fields may reproduce salient features
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### Gamma-ray bursts

**Bursting with controversy**

**Arguments continue about the biggest explosions in the universe**

**Gamma-ray bursts (GRBs)** are one of the most mysterious and controversial things astronomers can see. Mysterious, because for a long time there was no consensus about what caused them. Controversial, because even though there is now agreement about the underlying cause—supernovae—there is an argument about how such stellar explosions actually generate gamma rays.

These rays are an energetic form of electromagnetic radiation. (More familiar forms of this radiation include radio, light, and X-rays.) The idea is that a star is about to go supernova and that the release of energy is so strong that it can be detected far away. The radiation is produced over a period of time, typically less than a second, and it is detectable by telescopes on the ground and in space.

There are two theories about how the gamma rays in these bursts are generated. One is that they are a form of synchrotron radiation—the radiation produced when electromagnetic energy is trapped in a curved magnetic field. The other is that they are formed by an interaction between low-energy electromagnetic radiation, such as light, and high-energy charged particles produced in the explosion. This is a process known as inverse Compton scattering.

In the past year, two satellite observations that bear on this and other questions about GRBs have been made. One, in late March, was carried out by HETE-2, a multi-national satellite explicitly designed to search for GRBs. This burst was one of the closest to Earth that has ever been observed. Astronomers are now better able to see, in the position of HETE-2 predicted, the remains of a supernova. It was in this that confirmed supernovae as the cause of GRBs, rather than colliding neutron stars or even more exotic ideas such as events in the fabric of space.

The other observation, however, was in some ways more remarkable. It was made in December 2002 by RXTE, an American satellite actually designed to observe the sun. Serendipitously, a burst occurred in the same part of the sky as the sun, and RXTE saw it. But it is the accidental observation, not one made deliberately, that bears the question of what causes the gamma rays. This is because it allowed researchers to try to measure their polarisation.

**Tyring, though, is not the same as succeeding.** Wayne Coburn and Steven Boggs of the University of California, Berkeley, used the RXTE data to assert, in a paper published in May in Nature, that around 80% of the gamma rays in this particular burst were “linearly polarised”. According to a paper just published in *Astrophysical Journal* by Maxim Tyukov of McGill University in Montreal, his colleagues, that because the magnetic fields of the supernova were carrying the bulk of the energy of the burst. This suggests the gamma rays are generated by synchrotron radiation—a form of electromagnetic radiation that is produced when charged particles are moving at high speeds.

But a few weeks ago Robert Rutledge and Derek Fox of the California Institute of Technology (Caltech), Pasadena, came up with the opposite conclusion from the same set of data. They have written a paper in which they claim that Dr Coburn and Dr Boggs have made a mistake in their analysis. According to Dr Rutledge and Dr Fox, the data actually show negligible polarisation. Dr Coburn and Dr Boggs have written another paper defending their analysis, and say a more thorough defence is forthcoming.

**A yardstick for the future?**

The result from HETE-2 is remarkable enough, however, because it pinned the burst down so quickly and precisely. But how can we tell if GRBs have been hard to locate. This was because they are so bright that they were able to overwhelm the available detectors. But HETE-2 is a recently launched satellite, with a better detector, and because the burst it saw was relatively close by, it was fairly easy to locate the remnant, and thus examine them.

Although GRBs themselves last at most a few seconds, they are observed on timescales of milliseconds. Different supernovae, he concludes, release different proportions of their energy as gamma rays, and those differences are significant. A shame. But though they may turn out to be less useful than hoped for in answering the rest of the universe, GRBs still seem to be generating plenty of interest—and controversy—in their own right.