Polarization of Gamma–Ray Burst Optical and Near-Infrared Afterglows

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**Abstract.** Gamma–Ray Burst afterglow polarization measurements, in spite of their intrinsic difficulties, have been carried out for a number of events that begins to be adequate to draw some general statistical conclusions. Although the presence of some degree of intrinsic polarization seems to be well established, there are still open problems regarding the polarization time evolution and the possible contribution of polarization induced by dust in the host galaxies.

1. Why is polarimetry important for GRB afterglows?

Polarization from astrophysical sources is a typical signature for a number of physical phenomena (di Serego et al. 1997). In the context of gamma–ray burst (GRB) physics, the simple detection of some degree of polarization from an optical afterglow (Covino et al. 1999, Wijers et al. 1999; Fig. 1) has always been considered a clear signature for synchrotron emission. Time and wavelength variation of the polarization degree and position angle can be powerful probes for the physics and the dynamics of the expanding fireball and of the GRB environment.

1.1. How polarization can be produced in GRB afterglows

As a general rule, to produce observable polarization, some degree of anisotropy is necessarily required. Two general families of models have been developed to explain the level of polarization and its time evolution in GRB optical afterglows. One possibility is that the emission originates in causally disconnected regions of highly ordered magnetic field, each producing polarization almost at the maximum degree (Gruzinov & Waxman 1999; Gruzinov 1999; Medvedev & Loeb 1999; Loeb & Perna 1998). The observed polarization is then lowered by averaging over the unresolved source. Gruzinov & Waxman (1999) predicted a $\sim 10\%$ polarization. If the regions have a statistical distribution of energies, the
Table 1. The results of the 27 polarization measurements performed so far (January 2003). 1σ errors and 95% confidence level upper limits are reported. SP stands for spectropolarimetry. For GRB 020813 and GRB 021004 the reported polarization degrees and position angles are not yet corrected for Milky Way interstellar matter induced polarization.

| Burst         | P (%) | ϑ (°) | ∆t (hours) | Band | Ref. |
|---------------|-------|-------|------------|------|------|
| GRB 990123   | < 2.3 |       | 18         | R    | 1    |
| GRB 990510   | 1.7 ± 0.2 | 101 ± 3 | 18         | R    | 2    |
|               | 1.6 ± 0.2 | 96 ± 4  | 21         | R    | 3    |
|               | < 3.9  |       | 43         | R    | 3    |
| GRB 990712   | 2.9 ± 0.4 | 122 ± 4 | 11         | R    | 4    |
|               | 1.2 ± 0.4 | 116 ± 10 | 17        | R    | 4    |
|               | 2.2 ± 0.7 | 139 ± 10 | 35        | R    | 4    |
| GRB 991216   | < 2.7  |       | 35         | V    | 5    |
|               | < 5    |       | 60         | V    | 5    |
| GRB 010222   | 1.4 ± 0.6 |       | 22         | V    | 6    |
| GRB 011211   | < 2.0  |       | 37         | R    | 7    |
| GRB 020405   | 1.5 ± 0.4 | 172 ± 8 | 29         | R    | 8    |
|               | 9.8 ± 1.3 | 180 ± 4  | 31         | V    | 9    |
|               | 2.0 ± 0.3 | 154 ± 5  | 52         | V    | 10   |
|               | 1.5 ± 0.4 | 168 ± 9  | 78         | V    | 10   |
| GRB 020813   | 2.3 – 3.1 | 153 – 162 | 6         | SP   | 11   |
|               | 1.2 ± 0.2 | 158 ± 5  | 24         | V    | 12   |
|               | 1.6 ± 0.3 | 163 ± 6  | 29         | V    | 13   |
|               | 2.0 ± 0.4 | 179 ± 6  | 50         | V    | 13   |
|               | 4.3 ± 1.7 | 177 ± 11 | 96         | V    | 13   |
|               | < 5     |       | 11         | J    | 5    |
| GRB 021004   | 1.3 ± 0.1 | 114 ± 2  | 15         | V    | 14   |
|               | 1.3 ± 0.3 | 125 ± 1  | 16         | V    | 15   |
|               | 1.4 – 2.3 | 111 – 126 | 19        | SP   | 16   |
|               | 0.7 ± 0.2 | 89 ± 10  | 91         | V    | 17   |

1: Hjorth et al. 1999; 2: Covino et al. 1999; 3: Wijers et al. 1999; 4: Rol et al. 2000; 5: this paper; 6: Björnsson et al. 2002; 7: Covino et al. 2002d; 8: Masetti et al. 2002; 9: Bersier et al. 2003; 10: Covino et al. 2003a; 11: Barth et al. 2003; 12: Covino et al. 2002a; 13: Rol et al. 2003; 14: Covino et al. 2002b; 15: Rol et al. 2002; 16: Wang et al. 2003; 17: Covino et al. 2002c.

A position angle can be different at various wavelengths. This value is somewhat greater than what has been observed in GRB 990510, GRB 990712, GRB 010222, GRB 020405, GRB 020813 and GRB 021004. It is also greater than the upper limits derived for GRB 990123, GRB 990510, GRB 991216 and GRB 011211 (references in the caption of Tab. 1). All positive detections so far derived are below ∼3% (apart from one possible case, see Fig. 2) while the upper limits are lower than ∼5%.
In an alternative scenario proposed by Ghisellini & Lazzati (1999), Sari (1999), Granot et al. (2002), the magnetic field is ordered in the plane of the shock. In a spherical fireball, such a field configuration would give null polarization, but if a collimated fireball is observed off–axis (as it is most probable), a small degree of polarization is predicted, with a well defined time evolution. The light curve of the polarized emission has two peaks, with the position angle of the polarization vector shifting by 90° between them. Another important feature of the model is that the ratio of the polarized flux of the two peaks is related to the dynamics of the interaction of the jet with the interstellar medium. The polarization position angle should be in this case independent of the wavelength. Therefore, with a good time sampling of the polarization intensity and position angle the geometry and the dynamics of the jet can be efficiently pinned down.

Recently, Rossi et al. (2003; see also these proceedings) have predicted the polarization arising in structured jets when observed off–axis (Rossi, Lazzati & Rees 2002; Zhang & Mészáros 2002). Here the additional asymmetry is provided by the fact that the energy carried by the jet per unit solid angle is a function of the angle from the jet axis. In this model a single peak of polarized emission is predicted, with a constant polarization angle.

A small contribution to the observed polarization by dust in the host galaxy has not been completely ruled out. This could be the case if GRB progenitors are located in dusty star–forming regions. The key observational sequence to investigate on these possibilities involves multiband polarization measurements since the polarization induced by dust shows a well-defined wavelength dependence. Determining the time and the wavelength behavior of the polarization will therefore provide a wealth of new important information.

However, since polarization variability has been clearly singled out (e.g. in GRB 020813 and, possibly, in GRB 020405), a significant fraction of the polarization degree has to be intrinsic.
Figure 2. **Top panel:** Polarization degree and position angle for all the positive detections, i.e. upper limits are excluded. **Bottom panel:** \(Q\) and \(U\) Stokes' parameters for all the available data, i.e. including upper limits.
2. Some historical steps for GRB polarization measurements

Starting from 1999, at present (January 2003) 27 different polarization measurements have been performed, by studying 10 different optical and near infrared (NIR) afterglows. This resulted in 19 positive detections and 8 upper limits.

The first attempt to measure polarization for a GRB afterglow was carried out for GRB 990123 by Hjorth et al. (1999). Although in this case only an upper limit was derived (see Table 1), it was stringent enough to pose severe constraints to the various emission models. The problem immediately became not to explain how GRB optical afterglows (OA) can produce polarization, but why the polarization degree was so small (or possibly zero). The first successful polarization measurement came for the OA of GRB 990510: Covino et al. (1999) and Wijers et al. (1999) measured a polarization level at \( \sim 1.7\% \), therefore supporting the synchrotron emission scenario for the afterglows.

Few months later, Rol et al. (2000) were then able to carry out the first successful set of multiple polarization measurements reporting a polarization level around 2% for more than 20 hours, with a constant position angle and a marginal variation in intensity.

During the next couple of years several upper limits or marginal detections were derived: for GRB 991216 (this paper), GRB 010222 (Björsson et al. 2002) and GRB 011211 (Covino et al. 2002d). These findings again confirmed that the polarization degree up to a couple of days after the burst is always below few per cent. Attempts to measure polarization also in the NIR were carried out by Klose et al. (2001), but they provided weakly constraining upper limits of \( \sim 30\% \).

In 2002, three sets of observations (for GRB 020405, GRB 020813 and GRB 011004), produced a wealth of new information which are partly still under analysis. GRB 020405 was observed four times (Masetti et al. 2002, Bersier et al. 2003, Covino et al. 2002a) and three of these observations again give a roughly constant polarization degree (1.5 – 2%) and position angle. On the contrary, Bersier et al. (2003), two hours later than the measurement performed by Masetti et al., estimated \( \sim 10\% \). At present no model can explain such a sharp variation, if real.

Eventually, GRB 020813 and GRB 021004 were observed five times each, and spectropolarimetric observations were also derived (Barth et al. 2002; Wang et al. 2003; this paper). Data analysis is still in progress but preliminary results show that the polarization degree and position angle seem to be smoothly varying or roughly constant in the optical band. In both cases we hope that when the final results for the whole data sets will be fully available, the time coverage may be adequate enough to discriminate among different models and to derive some important physical parameters.

3. General considerations

The polarimetric and spectropolarimetric observations performed so far may allow to draw some statistical inference regarding polarization level and position angle for the observed GRB OAs from few hours up to 2–3 days after the \( \gamma \)-ray event. Fig. 2 shows the polarization degree and position angle for all positive
detections and the $Q$ and $U$ Stokes' parameters for all the performed observations (including upper limits). Apart from one controversial and therefore potentially interesting case (GRB020405, Bersier et al. 2003), all polarization measurements and upper limits show a polarization degree roughly below $\sim 3\%$. Any possible model has at least to be able to predict such a high probability to observe low or null polarization in the emission of GRB OAs observed starting from a few hours after the burst event.

References

Barth A.J., Sari R., Cohen M.H. et al. 2003, ApJ 584, L47
Bersier D., McLeod B., Garnavich M. et al. 2003, ApJ 583, L63
Björnsson G., Hjorth J., Pedersen K., Fynbo J.U. 2002, ApJ 579, 59
Covino S., Ghisellini G., Malesani D. et al. 2002b, GCN 1595
Covino S., Ghisellini G., Malesani D. et al. 2002c, GCN 1622
Covino S., Lazzati D., Ghisellini G. et al. 1999, A&A 348, L1
Covino S., Lazzati D., Malesani D. et al. 2002d, A&A 392, 865
Covino S., Malesani D., Ghisellini G. et al. 2002a, GCN 1498
Covino S., Malesani D., Ghisellini G. et al. 2003, A&A, in press (astro–ph/0211245)
Hjorth J., Björnsson G., Andersen M.I. et al. 1999, Science 283, 2073
di Serego Alighieri, S. 1997, in Instrumentation for Large Telescopes, ed. J. M. Rodriguez Espinosa, A. Herrero, & F. Sanchez (Cambridge University Press), 287
Ghisellini G. & Lazzati D. 1999, MNRAS 309, L17
Granot J., Panaitescu A., Kumar P., Woosley S.E. 2002, ApJ 570, L61
Gruzinov A. 1999, ApJ 525, L29
Gruzinov A. & Waxman E. 1999, ApJ 511, 852
Klose S., Stecklum B., Fischer O. 2001, Gamma–Ray Bursts in the Afterglow Era, eds. E. Costa, F. Frontera, J. Hjorth (Springer), 188
Loeb A. & Perna R. 1998, ApJ 495, 597
Masetti N., Palazzi E., Pian E. et al. 2003, this proceedings
Medvedev M.V. & Loeb A. 1999, ApJ 526, 697
Rol E., Wijers R.A.M.J., Vreeswijk P.M. et al. 2000, ApJ 544, 707
Rol E., Castro Cerón J.M., Gorosabel J. et al. 2002, GCN 1596
Rol E., Gorosabel J., Palazzi E. et al. 2003, this proceeding
Rossi E.M., Lazzati D. & Rees M.J., 2002, MNRAS, 332, 945
Rossi E.M., Lazzati D., Salmonson J.D. & Ghisellini G. 2002, Beaming and Jets in Gamma Ray Bursts, Copenhagen (astro-ph/0211020)
Sari R. 1999, ApJ 524, L43
Wang L., Baade D., Höflich P. & Wheeler J.C. 2003, A&AL, submitted (astro-ph/0301266)
Wijers R.A.M.J., Vreeswijk P. M., Galama T.J. et al. 1999, ApJ 523, L33
Zhang B. & Mészáros P., 2002, ApJ, 571, 876