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Polarization evolution of the GRB 020405 afterglow*

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Abstract. Polarization measurements for the optical counterpart to GRB 020405 are presented and discussed. Our observations were performed with the VLT–UT3 (Melipal) during the second and third night after the gamma–ray burst discovery. The polarization degree (and the position angle) appears to be constant between our two observations at a level around $1.5 \div 2\%$. The polarization can be intrinsic but it is not possible to unambiguously exclude that a substantial fraction of it is induced by dust in the host galaxy.

Key words. gamma rays: bursts – polarization – radiation mechanisms: non-thermal

1. Introduction

Polarimetric observations are a unique tool to single out different physical processes. In the context of gamma-ray burst (GRB) afterglow emission, some degree of polarization is expected to emerge in the optical flux as a signature of synchrotron radiation (Mészáros & Rees 1997). The observation of power-law decaying lightcurves (e.g. Wijers et al. 1997) and of power-law spectral energy distribution (e.g. Wijers & Galama 1999; Panaitescu & Kumar 2001) give also further support to the external shock synchrotron emission scenario.

The first successful polarization measurement was achieved for the optical afterglow (OA) of GRB 990510 (Covino et al. 1999; Wijers et al. 1999). Some months later, Rol et al. (2000) could perform three distinct observations for GRB 990712, showing a possible variation in the polarization degree, but with constant position angle. More recently, GRB 020813 showed definitely a highly significant variation in the polarization level, again with constant position angle (Barth et al. 2002; Covino et al. 2002a). Last, for GRB 021004, different measurements were performed (Covino et al. 2002b,c; Rol et al. 2002), but the results are still ambiguous because of the large Galactic-induced polarization. For all these observations, the polarization degree was always in the range $(0.8 \div 3)\%$.

For three further GRBs, GRB 990123 (Hjorth et al. 1999), GRB 011211 (Covino et al. 2002d) and GRB 010222 (Björnsson et al. 2002), upper limits are again consistent with a maximum value of $\sim$3% (95% confidence limit).

As a general rule, some degree of asymmetry in the expanding fireball is necessary to produce some degree of polarized flux. Gruzinov & Waxman (1999) argued that if the magnetic field is globally random but with a large number of patches where the magnetic field is instead coherent, a polarization degree up to $\sim$10% is expected, especially at early times. Ghisellini & Lazzati (1999) and, independently, Sari (1999) considered a geometrical setup in which a beamed fireball is observed slightly off-axis. This break of symmetry again results in a significant polarization. This model also predicts a testable variation of the polarization degree and position angle associated with the evolution of the afterglow lightcurve.

GRB 020405 was localized on 2002 April 5 at 00:41:26 UT by the interplanetary network (IPN) (Hurley et al. 2002). The burst showed a duration of $\sim$40 s and therefore belongs to the class of long duration bursts (Hurley et al. 1992). The optical counterpart was identified by Price et al. (2002a,b) 17.3 hours after the burst as an $R \sim 18.9$ source located at the coordinates $\alpha_{2000} = 13^{\mathrm{h}}58^{\mathrm{m}}03\overset{\mathrm{s}}{.}12$, $\delta_{2000} = -31°22'22\overset{''}{.}2$.

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VLT observations allowed to determine the redshift of $z = 0.695 \pm 0.005$ (Masetti et al. 2002a) and to discover the bright host galaxy (Masetti et al. 2002b). A new radio source was found at the above coordinates by the VLA (Berger et al. 2002), with a flux of 0.49 mJy at 8.46 GHz.

In addition to those presented here, polarimetric observations were performed by Masetti (2002c) with the VLT and by Bersier et al. (2002) with the Multiple Mirror Telescope, beginning 1.2 and 1.3 days after the GRB, respectively. Even if these two measurements were almost simultaneous, their results are in remarkable contrast. The first group found a level of polarization $P = (1.5 \pm 0.4)\%$ (hereafter 1-σ uncertainties are reported) with position angle $\vartheta = (172 \pm 8)°$, similar to other GRBs, while the second group reported the unprecedented high value $P = (9.89 \pm 1.3)\%$ at $\vartheta = (179.9 \pm 3.8)°$. We note however that the results of both groups are not yet published in a refereed journal.

2. Data and analysis

Our observations of GRB 020405 were obtained with the ESO's VLT–UT3 (Melipal), equipped with the Focal Reducer/low dispersion Spectrometer (FORS 1) and a Bessel filter V in the imaging polarimetry mode. Our first observation (hereafter run 1) started on April 7, 03:33 UT (2.1 days after the burst) and lasted ~3 hours. At the beginning of this observation the V magnitude was 21.82 ± 0.02, with respect to the USNO–A2.0 stars 0525_16813005 and 0525_16815468 (Simoncelli et al. 2002). Our second observation (run 2) was performed during the following night, starting April 8, 4:01 UT (3.2 days after the burst), and lasted ~3.5 hours. The V magnitude of the OA was 22.45 ± 0.05 again with respect to the two above reported stars[1]. Observations were performed under good seeing conditions (0.5″–0.9″) in standard resolution mode with a scale of 0.2″/pixel (Fig. 1).

Standard stars were also observed. One polarized, Hiltner 652, in order to fix the offset between the polarization and the instrumental angles, and one non-polarized, WD 1615–154, to estimate the degree of artificial polarization possibly introduced by the instrument.

The data reduction was carried out with the `Eclipse` package (version 4.2.1, Devillard 1997). After bias subtraction, non-uniformities were corrected using flat-fields obtained with the Wollaston prism. The flux of each point source in the field of view was derived by means of both aperture and profile fitting photometry by the `DAOPHOT II` package (Stetson 1987), as implemented in `ESO–MIDAS` (version 01SEP) and the Graphical Astronomy and Image Analysis (`GAIA`) tools[2]. For relatively isolated stars the various applied photometric techniques differ only by a few parts in a thousand. The general procedure followed for FORS 1 polarization observation analysis is extensively discussed in Covino et al. (1999, 2002d).

[1] Note a difference by ~0.4 mag with respect to our previous measurement (Covino et al. 2002e), due to preliminary calibration to USNO–A2.0 magnitudes.

[2] `http://star-www.dur.ac.uk/~pdraper/gaia/gaia.html`

Table 1. Polarization degree P and positional angle ϑ for the optical counterpart to GRB 020405. Observations were performed with the VLT–UT3 (Melipal) in the Bessel V-band filter.

Run	UT	V mag	P (%)	ϑ (°)
1	Apr 7.212	21.82 ± 0.02	1.96 ± 0.33	154 ± 5
2	Apr 8.297	22.45 ± 0.05	1.47 ± 0.43	168 ± 9

The average polarization of the field stars is low as shown by the normalized Stokes parameters Q and U: $\langle Q \rangle = -0.0021 \pm 0.0009$ and $\langle U \rangle = 0.0012 \pm 0.0009$, corresponding to $P = (0.24 \pm 0.09)\%$.

The degree P and angle ϑ of polarization are obtained from the measurements of Q and U for the OA $\left[P = \sqrt{U^2 + Q^2}, \vartheta = \frac{1}{2}\arctan(U/Q)\right]$ after correcting for the polarization induced by the instrument or by the local interstellar matter. Moreover, for any low level of polarization ($P/\sigma \leq 4$), a correction which takes into account the bias due to the fact that P is a definite positive quantity (Wardle & Kronberg 1974) is required. At low polarization level, the distribution function of P (and of ϑ, the polarization angle) is no longer normal and that of P becomes skewed (Clarke et al. 1983; Simmons & Stewart 1985; Fosbury et al. 1993).

We then corrected our measurements for this bias (Simmons & Stewart 1985) and derived the normalized polarization Stokes parameters for the OA: $Q = 0.0126 \pm 0.0033$ and $U = -0.0150 \pm 0.0033$ for run 1 and $Q = 0.0137 \pm 0.0043$ and $U = -0.0054 \pm 0.0044$ for run 2. From these values of Q and U we have derived the polarization degree P and positional angle ϑ for both run 1 and 2, as reported in Table 1. Monte Carlo simulations confirmed the reported values and uncertainties.

2.1. Host galaxy contamination to photometry

Figure 1 clearly shows that the OA is superimposed to a rather bright and extended galaxy (~4″ × 7″ in our VLT images, with some bright knots). Since the light of the galaxy is unavoidably mixed with that of the OA, it is important to estimate the effect of this contamination on the polarization angle and degree. If the emission of the galaxy is not polarized, the net effect is to effectively reduce the degree of polarization of the OA. It is easy to show that the observed polarization degree $P_{\rm obs}$ can be corrected to yield the intrinsic value $P_{\rm true}$, if we know the contributions to the total flux of the galaxy, $F_{\rm gal}$, and of the OA, $F_{\rm OA}$:

$$P_{\rm true} = \left(1 + \frac{F_{\rm gal}}{F_{\rm OA}}\right) P_{\rm obs} = \frac{F_{\rm tot}}{F_{\rm OA}} P_{\rm obs}, \quad (1)$$

where $F_{\rm tot} = F_{\rm OA} + F_{\rm gal}$. The polarization angle is of course not affected, even if the lower value of P eventually leads to a larger uncertainty.

To estimate the contribution of the galaxy within the point spread function (PSF), it is necessary to analyze late-time images, when the flux of the afterglow gives only a negligible contribution. For GRB 020405, only a rough R magnitude is reported to date (Bersier et al. 2002; see also Price et al. 2002c),

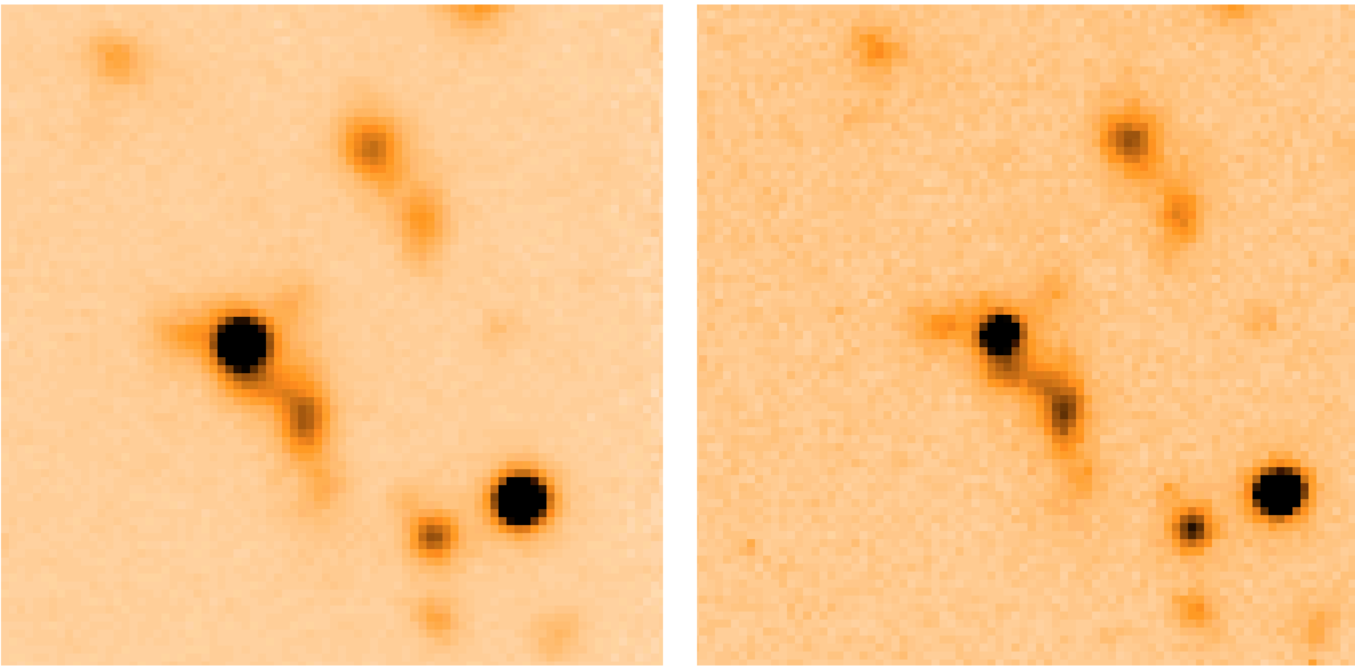

Fig. 1. The optical afterglow of GRB 020405 superimposed to the host galaxy during run 1 (left) and run 2 (right). Pictures were obtained composing the polarization images in the Bessel V-band filter. Box size is about $18'' \times 18''$; North is up and East is left. The OT is marked by an arrow.

suggesting that in the PSF area $V \geq 24$ depending on the color of the galaxy (e.g. Fukugita et al. 1995).

Although an accurate analysis of the late-time image would be required, the good seeing conditions in our images make these corrections, estimated by Eq. (1), essentially negligible.

3. Discussion

In Fig. 2 we show the time evolution of the polarization level P and angle ϑ for GRB 020405, also including the measurements performed by Bersier et al. (2002) and by Masetti et al. (2002c). Because of the striking contrast between the observations of the first night, the question for variability cannot be firmly settled. However, no significant variation is found by looking at our data alone (second and third night). Our points are moreover fully consistent with the one of Masetti et al. (2002c).

A certain amount of (constant) polarization can be introduced by intervening dust along the line of sight, either in our Galaxy or in the host. The values reported in Table 1 are already corrected for the (low) Galactic contribution. If additional dust is present in the host galaxy, its presence should be revealed through spectral reddening. Since the induced polarization should not be larger than $P_{\max} = 9\% \, E_{B-V}$ (Serkowski et al. 1975), a reddening $E_{B-V} \approx 0.2$ (in the host frame) would be required to explain our value $P \approx 2\%$. This transforms into $A_V \sim 0.6 \div 1.1$ depending on the selective-to-total extinction coefficient R_V, that can be higher than the standard value ~3.1 in star-forming regions (see e.g. Cardelli et al. 1989). X–ray data by *Chandra* (Mirabal et al. 2002) indeed reveal the presence of some material along the line of sight, with $N_{\rm H} = (4.7 \pm 3.7) \times 10^{21}$ cm^{-2}. Assuming a Galactic dust-to-gas ratio, this corresponds to $A_V = 2.8 \pm 2.2$

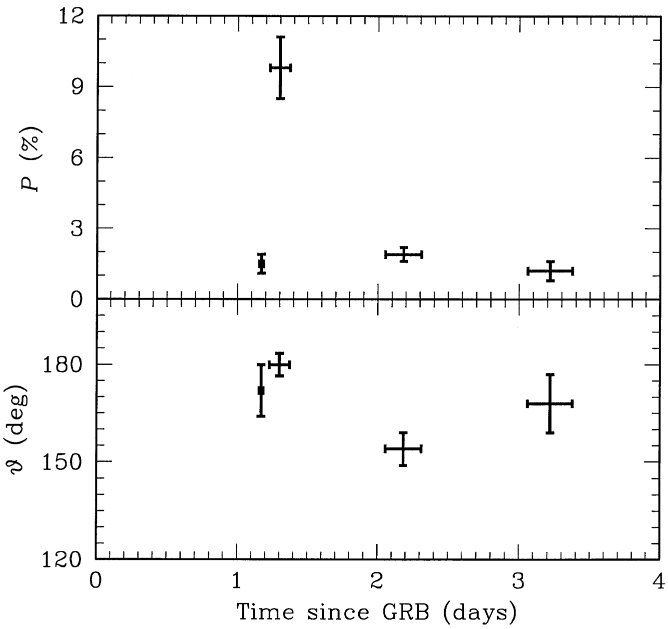

Fig. 2. Time evolution of the polarization level P and position angle ϑ. Data for the first night are from Masetti et al. (2002c) and from Bersier et al. (2002).

(Predehl & Schmitt 1995). The effect of dust on the polarization degree can therefore be significant. This shows that the study of polarization can yield important constraints about the medium surrounding the GRB progenitor.

In addition to the difficulty of assessing the intrinsic level of polarization of the OA, interpreting the polarization measurements within the framework of the proposed models is made difficult by the lack of a clear break in the power–law decay of the lightcurve. In fact, despite some claims of the possible presence of a jet break at early times ($t_{\rm j} \sim 1$ day, Price et al. 2002c), the data seem also compatible with a single power-law up to ten days after the burst (Masetti et al. 2002b).

In the framework of the patchy model (Gruzinov & Waxman 1999), a moderate-high level of polarization is expected. The level of polarization should monotonically decay as a function of time due to the increase of the visible surface of the fireball (and therefore to the increased number of visible patches). The position angle of the polarization vector should fluctuate randomly. Since the polarization predicted in this model is $P \sim 60\% / \sqrt{N}$, the inferred number of patches is $N \sim 1000$.

In the case of collimated fireballs, Ghisellini & Lazzati (1999) and Sari (1999) proposed a model in which the polarized fraction has a more complex behaviour, with two peaks separated by a moment of null polarization that roughly coincides with the break time of the total flux lightcurve. Lacking a robust detection of a jet break and given the limited number of measurements, only a qualitative comparison can be performed. Again, the measurement of Bersier et al. (2002) cannot be reconciled with the model in any case and, if real, should be ascribed to some still unknown effect (see Bersier et al. 2002 for a comprehensive discussion).

In the case of a late time break ($t_{\rm j} > 10$ d), our measurements can be interpreted to belong to the first peak of the polarization curve (see Fig. 4 in Ghisellini & Lazzati 1999), with the moderate decay of the polarization being an indication that the break time is approaching. If the break were at early times ($t_{\rm j} \leq 1$ d; see Price et al. 2002c), the absence of a rotation of 90° of the position angle that is predicted between the first and the second peak in the polarization time evolution (e.g. Ghisellini & Lazzati 1999; Sari 1999) would point either to a rapidly sideways expanding jet (Sari 1999) or to a structured jet (Rossi et al. 2002a,b).

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