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Polarimetric observations of GRB 011211*

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Abstract. We present and discuss polarimetric observations performed with the VLT–UT3 (Melipal) on the afterglow of GRB 011211, ~35 hours after the burst onset. The observations yielded a 3 σ upper limit of $P < 2.7\%$. We discuss this result in combination with the lightcurve evolution, that may show a break approximately at the time of our observation. We show that our upper limit is consistent with the currently favored beamed fireball geometry, especially if the line of sight was not too close to the edge of the cone.

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

1. Introduction

It is now generally believed that the afterglow ubiquitously observed in GRBs is produced by synchrotron radiation (see, e.g., Piran 1999) as a beamed relativistic fireball is decelerated by the impact with the ambient medium (Mészáros & Rees 1997). This interpretation is confirmed by the observation of power-law decaying lightcurves (Wijers et al. 1997) showing a break at $t \sim 1$–30 days (Frail et al. 2001), of power-law spectral energy distributions (Wijers & Galama 1999; Panaitescu & Kumar 2001) and of linear polarization (Covino et al. 1999; Wijers et al. 1999; Rol et al. 2000).

The derivation of the fireball opening angle from the time of breaks in the afterglow lightcurves is crucial to derive the energy budget of GRBs (Frail et al. 2001). It is nevertheless a matter of open debate whether the breaks are due to collimation or to different hydrodynamical transitions (Moderski et al. 2000; in 't Zand et al. 2001). The presence of polarization, and in particular its evolution (Ghisellini & Lazzati 1999, hereafter GL99; Sari 1999) is an alternative and unbiased way to prove that the fireball is beamed and allows to constrain the orientation of the jet with respect to the line of sight to the observer (GL99; Björnsson & Lindfors 2000).

Before the observation presented here, 4 GRBs have been observed in polarimetric mode at various wavelengths, yielding two positive measurements and two upper limits. The first measurement was performed on the afterglow of GRB 990123 in the R band, yielding an upper limit $P < 2.3\%$ (95% confidence level, Hjorth et al. 1999). The first detection of linear polarization was obtained by Covino et al. (1999) on GRB 990510. Observations in the R band at $t \sim 18.5$ hours after the burst yielded $P = (1.7 \pm 0.2)\%$. The detection was confirmed by Wijers et al. (1999), who obtained $P = (1.6 \pm 0.2)\%$ at $t \sim 20$ hours, a value consistent with that of Covino et al. (1999). Multiple measurements of polarization at three different epochs were performed on GRB 990712 (Rol et al. 2000). While the position angle did not vary significantly (but the data are also consistent with a 45° variation), a marginal detection of fluctuation of the polarized fraction was obtained, the second measurement ($P = (1.2 \pm 0.4)\%$ at $t \sim 16.7$ hours) being smaller than the other two ($P = (2.9 \pm 0.4)\%$ and $P = (2.2 \pm 0.7)\%$ at $t \sim 10.6$ hours and $t \sim 34.7$ hours, respectively). Finally, an attempt to measure near infrared (NIR) polarization in the afterglow of GRB 000301C yielded only a weak $P < 30\%$ constraint[1] (Stecklum et al. 2001).

As a general rule, some degree of asymmetry is necessary in order to observe polarization. Two general models have been proposed to explain some degree of linear polarization in the framework of synchrotron emission. Gruzinov & Waxman (1999) discuss how ordered magnetic field domains can diffuse in the fireball, predicting $P \sim 10\%$. GL99 (and, independently,

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[1] Several other attempts to measure linear polarization of afterglows in the NIR were performed by the same collaboration, but it turned out that for all these bursts an optical–IR afterglow was not detected.

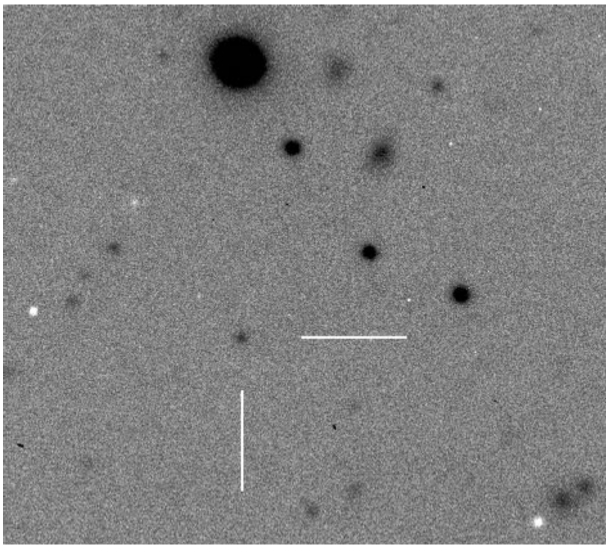

Fig. 1. The optical afterglow to GRB 011211 in the Bessel V-band VLT–UT3 acquisition frame.

Sari 1999) considered a geometrical setup in which a beamed fireball observed slightly off-axis provides the necessary degree of anisotropy (see also Sect. 3). Variable polarization up to 10% is predicted.

2. Data and analysis

GRB 011211 was detected by *Beppo*SAX on Dec. 11, 19:09:21 UT and initially classified as part of the X–ray rich class (Gandolfi 2001). Refined analysis (Frontera et al. 2002) showed that it was actually a standard GRB. The optical afterglow was discovered after 10 hours (Grav et al. 2001) and confirmed by Bloom & Berger (2001).

Our observations of GRB 011211 were obtained at ESO's VLT–UT3 (Melipal), equipped with the Focal Reducer/low dispersion Spectrometer (FORS) and Bessel filter R. The OT associated with GRB 011211 was observed for ~3 hours, starting ~35 hours after the burst, when the V- and R-band magnitudes were 21.70 ± 0.06 and 21.43 ± 0.1, with respect to the USNO star U0675_11427359 (Covino et al. 2002; Henden 2002). Observations were performed in standard resolution mode with a scale of 0.2″/pixel (Fig. 1); the seeing varied from ~1.4″ at the beginning to ~0.7″ at the end. The observation log is reported in Table 1.

Imaging polarimetry is achieved by the use of a Wollaston prism splitting the image of each object in the field into the two orthogonal polarization components which appear in adjacent areas of the CCD image. For each position angle $\phi/2$ of the half–wave plate rotator, we obtain two simultaneous images of cross-polarization, at angles ϕ and $\phi + 90°$.

Relative photometry with respect to all the stars in the field was performed and each couple of simultaneous measurements at orthogonal angles was used to compute the U and Q Stokes parameters. This technique removes any difference between the two optical paths (ordinary and extraordinary rays) and the polarization component introduced by Galactic interstellar grains along the line of sight. Moreover, since the Stokes parameters are directly derived from the source intensity ratio between the ordinary and extraordinary beams which are recorded simultaneously, they are not influenced by intensity variations of the source, provided that the polarization remained constant during the exposure time. If the polarization has varied, what is obtained is the average of the Stokes parameters during the measurement (for further details on the reduction algorithm applied to data obtained with a dual–beam instruments like the FORS1 see e.g. Cohen et al. 1997; di Serego Alighieri 1997).

With the same procedure, we observed also one polarimetric standard star, Vela1 95, in order to fix the offset between the polarization and the instrumental angles.

The data reduction was carried out with the ESO-MIDAS (version 01SEP) system. 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 MIDAS. For relatively isolated stars the two techniques differ only by a few parts in a thousand.

In Fig. 2 we plot on the plane defined by the normalized Stokes parameters Q and U the results of the polarization

Table 1. Observation log for the polarimetric observation of the GRB 011211 field.

Starting time UT, 13 Dec. 2001	**Exposure** s	**Angle** deg	**Filter**	**Seeing** arcsec
05:40	720	00.0	R	1.4
05:53	720	22.5	R	1.2
06:06	720	45.0	R	1.0
06:19	720	67.5	R	1.0
06:34	720	00.0	R	1.0
06:47	720	22.5	R	0.9
07:00	720	45.0	R	0.8
07:13	720	67.5	R	0.8
07:45	720	00.0	R	0.8
07:58	720	22.5	R	0.8
08:15	720	45.0	R	0.8
08:28	720	67.5	R	0.7

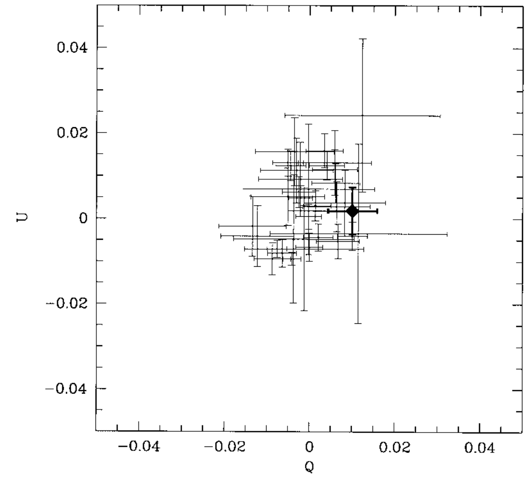

Fig. 2. Polarization normalized Stokes parameters U and Q for GRB 011211 optical transient (bold cross) and stars in the field.

measurements performed for the optical transient and for most of the stars in the field of view. The average polarization of the stars is consistent with zero: $\langle Q \rangle = -0.0015 \pm 0.0008$ and $\langle U \rangle = -0.0007 \pm 0.0007$. The normalized polarization Stokes parameters for the optical transient are $Q = 0.0101 \pm 0.0058$ and $U = 0.0018 \pm 0.0055$. The formal degree of polarization could in principle be obtained from the measurements of Q and U ($P = \sqrt{U^2 + Q^2}$) after correcting for the instrumental or local interstellar polarization ($\langle Q \rangle$ and $\langle U \rangle$). However, for very low level of polarization ($P/\sigma \le 4$), 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) are no longer normal and that of P becomes skewed (Clarke et al. 1983; Simmons & Stewart 1985; Fosbury et al. 1993). We therefore corrected the bias following Simmons & Stewart (1985) and derived a 3 σ upper limit of 2.7% (2.0% at 95% confidence level) for the polarization degree of the optical transient of GRB 011211. Monte Carlo simulations confirmed the reported upper limits[2].

3. Modeling

Linear polarization measurements have been performed, to date, in 5 afterglows. Even though theoretical models predict that the degree of the polarization can be as high as 10% (Gruzinov & Waxman 1999; GL99; Sari 1999), the afterglows seem to show only a few per cent of polarization, if any.

In the model of Gruzinov & Waxman (1999), a smaller polarization can be explained by increasing the number of ordered magnetic field domains $N_{\rm dom}$, since $P \sim 60/\sqrt{N_{\rm dom}}$. In the beamed fireball model, the polarization is due to the geometric asymmetry provided by a beamed fireball observed off-axis. The degree of polarization depends on the ratio of the angle between the line of sight and the cone axis ($\theta_{\rm o}$) to the opening angle of the jet ($\theta_{\rm c}$). In addition, the degree of linear polarization is time dependent, with two separate peaks (the first always smaller than the second) spaced by a moment of null polarization. In this moment the position angle of the polarization vector abruptly changes by 90°. The expected degree of polarization can then be computed by constraining the fireball geometry. In Fig. 3 we show the predictions of the model as a function of the ratio $\theta_{\rm o}/\theta_{\rm c}$ and of the ratio $t/t_{\rm B,0}$, where t is the observed time and $t_{\rm B,0}$ is the break time that an observer at $\theta_{\rm o} = 0$ would measure in the lightcurve. Note that in the original Fig. 4 of GL99, the polarization was shown as a function of the inverse of the Lorentz factor. Since, however, both the break time and the linear polarization are functions of the geometrical properties of the jet only, the observed polarization is a function of $t/t_{\rm B,0}$, without loss of generality (Sari 1999).

Holland et al. (2002) claim the detection of a break in the optical lightcurve of GRB 011211 at $1.5 < t < 2.7$ days; this is confirmed also by later measurements at $t \gtrsim 10$ d (Burud et al. 2001; Fox et al. 2002). If such break is indeed due to collimation in the outflow, our polarimetric observation was performed

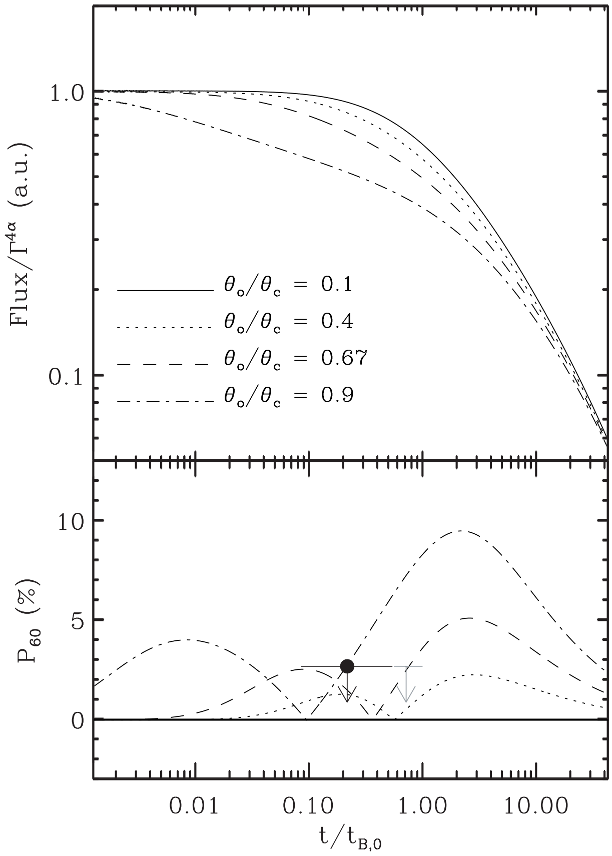

Fig. 3. Lightcurves (upper panel) and linear polarization (lower panel) of the OT as a function of the ratio of the observation time over the break time $t_{\rm B,0}$, as measured by an observer along the symmetry axis of the jet ($\theta_{\rm o}/\theta_{\rm c} = 0$). Different lines are relative to different off-axis position of the line of sight (see text and indications in the figure). The black upper limit shows the position of our measurement if GRB 011211 follows the correlation of Frail et al. (2001), while the gray upper limit refers to the lightcurve break detected by Holland et al. (2002).

at $0.5 < t/t_{\rm B,0} \lesssim 1$. The upper limit is shown with a grey arrow in Fig. 3. Our upper limit is then consistent with the model prediction for $\theta_{\rm o} < 0.67\ \theta_{\rm c}$. Since half of the random oriented observers satisfy this constraint, our upper limit is fully consistent with the theory of jetted fireballs.

However, the analysis of the broad-band spectrum taken on Dec. 12.3 (∼1 day before our polarization measurement), including data in the optical (Holland et al. 2002) and X–ray bands (Reeves et al. 2002; Borozdin & Trudolyubov 2002), requires the presence of a spectral break at about $\nu_{\rm b} \sim 10^{15}$ Hz, very close to the optical band (Fig. 4). In the context of the standard synchrotron model (Sari et al. 1998), this can be interpreted either as the injection frequency (in the fast cooling regime) or the cooling frequency (in the slow cooling regime). In the first case, the low-energy spectral index should be $\alpha_{\rm o} = 0.5$, consistent with the observed value 0.6 ± 0.15, while in the second case the difference between the high- and low-energy slopes should be $\alpha_{\rm X} - \alpha_{\rm o} = 0.5$, also consistent with the observed one 0.53 ± 0.15. Most afterglow models predict that $\nu_{\rm b}$ should decrease with time, yielding a *chromatic* break in the lightcurve, expected soon after Dec. 12.3. The time needed for

[2] In Covino et al. (2002) we reported a preliminary 3 σ upper limit slightly lower: 2.5%.

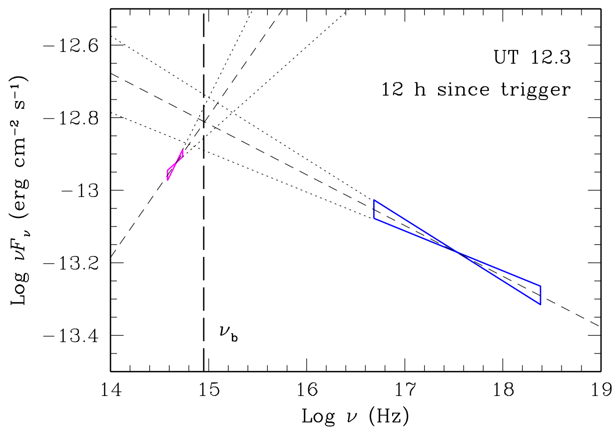

Fig. 4. Broad-band optical to X–ray spectrum on Dec. 12.3 UT. Optical data (corrected for Galactic extinction) are from Holland et al. (2002), while X-ray data are from Borozdin & Trudolyubov (2002). The low- and high-energy spectral index ($F_\nu \propto \nu^{-\alpha}$) are $\alpha_o = 0.6 \pm 0.15$ and $\alpha_X = 1.1 \pm 0.03$ (note that the plot is in νF_ν, so the slopes are diminished by one unity). A spectral break is present at $\nu_b \sim 10^{15}$ Hz.

ν_b to pass through the optical band is ~1 d, and the lightcurve is not sampled enough to discriminate between the chromatic and achromatic case. The case for a chromatic break receives some support from the analysis of the temporal behaviour of the afterglow. In fact, the observed flux decreases with time, following the power-law trend $F_\nu \propto t^{-\delta_\nu}$, where $\delta_o = 0.83 \pm 0.04$ in the optical band and $\delta_X = 1.6 \pm 0.1$ in the X–ray band (Holland et al. 2002; Borozdin & Trudolyubov 2002). The change in the decay slope after the passage of ν_b through the optical band is hence predicted to be $\Delta = \delta_X - \delta_o = 0.77 \pm 0.1$, fully consistent with the value observed by Holland et al. (2002): $\Delta_{obs} \geq 0.6$.

We can derive a second estimate for the jet break time using the energy vs. break time correlation (Frail et al. 2001). Using Fig. 3 of Bloom et al. (2001), we derive a bolometric isotropic energy $E_{iso,bol} \sim 10^{53}$ erg from the (40–700) keV energy release $E_{iso} \sim 6 \times 10^{52}$ erg (Frontera et al. 2002). We can then estimate the expected jet–break time, which turns out to be (allowing for a factor of two uncertainty in the beaming-corrected total energy), $3 < t_B < 18$ d. This time is therefore much later than the time $t_{pol} \sim 1.5$ d at which the polarization measurement was performed. This estimate of jet-break time, converted into $t/t_{B,0}$, is shown by the black arrow in Fig. 3. This figure shows that the polarization measurement was probably performed when the polarized fraction was at its minimum for possibly all the fireball configurations.

4. Conclusions

We have observed in polarimetric mode the optical afterglow of GRB 011211; our result is a 3 σ upper limit of $P < 2.7\%$. This is consistent with previous measurements performed on other GRBs. Unfortunately a clear achromatic jet break is not observed in the burst lightcurve, and this does not allow us to perform a clear comparison with the currently favored theoretical models for the production of polarization in beamed fireballs. We can nevertheless deduce that, if the ratio of the observing angle to the jet opening angle was less than 2/3, our measurement would be consistent with the models. This result holds true if a break was present at $t \sim 2$ days (Holland et al. 2002) or if it was at a much later time.

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