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DETECTION OF POLARIZATION IN THE AFTERGLOW OF GRB 990510 WITH THE ESO VERY LARGE TELESCOPE

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ABSTRACT

Following a *BeppoSAX* alert and the discovery of the OT at SAAO, we observed GRB 990510 with the FORS instrument on ESO's VLT Unit 1 (Antu). The burst is unremarkable in gamma rays, but in optical is the first one to show good evidence for jetlike outflow. We report the detection of significant linear polarization in the afterglow: it is 1.6 ± 0.2% 0.86 days after trigger, and after 1.81 days is consistent with that same value, but much more uncertain. The polarization angle is constant on a timescale of hours and may be constant over one day. We conclude that the polarization is intrinsic to the source and due to the synchrotron nature of the emission, and discuss the random and ordered field geometries that may be responsible for it.

Subject headings: gamma rays: bursts — magnetic fields — polarization — radiation mechanisms: nonthermal

1. INTRODUCTION

It is now well established that gamma-ray burst (GRB) afterglows are the result of relativistic blast waves (Rees & Mészáros 1992; Mészáros & Rees 1997; Wijers, Mészáros, & Rees 1997; Waxman 1997a; Sari, Piran, & Narayan 1998; see Piran 1999 for a review) emitting primarily synchrotron radiation (Galama et al. 1998a, 1998b; Wijers & Galama 1999). Synchrotron radiation is highly polarized, with typical degrees of (linear) polarization for ordered magnetic fields of ∼60% (Hughes & Miller 1991), and one should therefore not be surprised if GRB afterglows show a measurable amount of polarization. If the shock takes place in a collimated outflow (jet) one might expect, by analogy to what is observed for jets in AGNs, degrees of linear polarization of 10%–20% (Angel & Stockman 1980; Muxlow & Garrington 1991). The strong intrinsic polarization of this emission is lowered by averaging over the unresolved source (Gruzinov & Waxman 1998; Gruzinov 1999; Medvedev & Loeb 1999; Loeb & Perna 1998), and thus far only an upper limit of 2.3% to afterglow polarization has been set, for GRB 990123 (Hjorth et al. 1999). Here we report the results of our optical polarimetric observations of the afterglow of GRB 990510, one and two days after trigger. We detect significant polarization on day one, similar in magnitude and position angle to the value obtained by Covino et al. (1999a, 1999d) that same night.

The prompt gamma-ray emission from GRB 990510 was detected with BATSE on *CGRO* on 1999 May 10.367 UT (Kippen et al. 1999), with *Ulysses* (Hurley & Barthelmy 1999), and with the GRBM on *BeppoSAX* (Amati et al. 1999). The BATSE flux history (Fig. 1) shows multiple peaks and a duration (T_{90}) of 68 s. The peak energy flux (25–2000 keV) was $(5.19 \pm 0.96) \times 10^{-6}$ ergs cm^{-2} s^{-1}, ranking it in the top 4% among BATSE GRBs. The fluence is $(2.29 \pm 0.07) \times 10^{-5}$ ergs cm^{-2}, placing it in the top 9% of the BATSE distribution. Assuming $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_0 = 0.3$, and $\Lambda = 0$, we deduce a peak luminosity $L_\gamma = 7.3 \times 10^{52}$ ergs s^{-1} and total energy release $E_\gamma = 1.2 \times 10^{53}$ ergs (for $z = 1.62$ and isotropic emission). The time integrated fit to the entire burst gives a peak energy (as defined in Band et al. 1993) $E_p = 147 \pm 4$ keV, placing it in the center of the BATSE E_p distribution (Malozzi et al. 1995). The burst is therefore unremarkable in gamma rays both with respect to the entire BATSE catalog and with respect to other bursts with detected afterglows.

GRB 990510 was located by the WFC on board *BeppoSAX* (Dadina et al. 1999) and its X-ray afterglow was detected by *BeppoSAX* as well (Kuulkers et al. 1999). The position of the WFC X-ray source is R.A. = $13^h38^m06^s$, decl. = $-80°29'.5$ (equinox 2000.0), with an error radius of 3′ (Piro 1999a). With the 1 m telescope at the South African Astronomical Observatory (SAAO) we started imaging the error region at May 10.72, roughly 8.5 hr after the burst. Comparison with the Digitized Sky Survey revealed a previously unknown object at R.A. = $13^h38^m07^s.62$, decl. = $-80°29'48''.8$ (Vreeswijk et al. 1999a). Following the identification we took low-resolution spectra at the VLT of the optical transient (OT), setting a lower limit to the redshift of $z = 1.619 \pm 0.002$ through the identification of redshifted absorption lines (Vreeswijk et al. 1999b). Numerous photometric observations show that the light curve is well-described by a power law with a break occurring about 1.5 days after the burst (Stanek et al. 1999; Harrison et al. 1999; Fig. 2), which may be the result of beaming (Rhoads 1999; Mészáros & Rees 1999; Sari et al. 1999).

We report our polarimetric analysis and its results in § 2, discuss possible interpretations in § 3, and then summarize our findings.

2. POLARIMETRIC OBSERVATIONS

Optical polarization observations of GRB 990510 were obtained with the FOcal Reducer/low dispersion Spectrograph 1 (FORS1) on the European Southern Observatory's (ESO) 8.2

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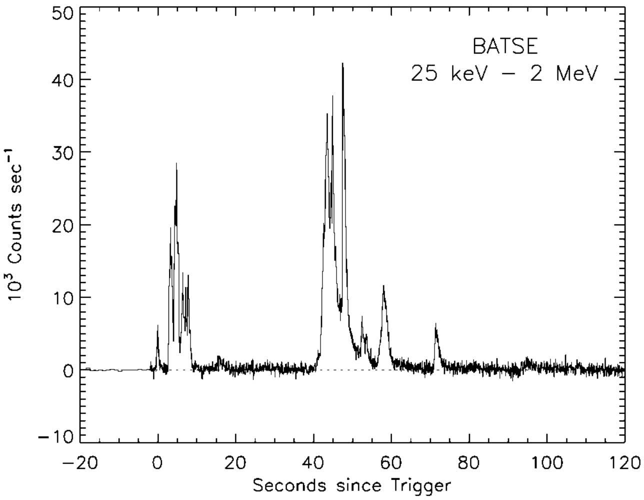

FIG. 1.—Time history of GRB 990510 integrated over the four BATSE discriminator energy channels (25 keV–2 MeV) at 64 ms time resolution.

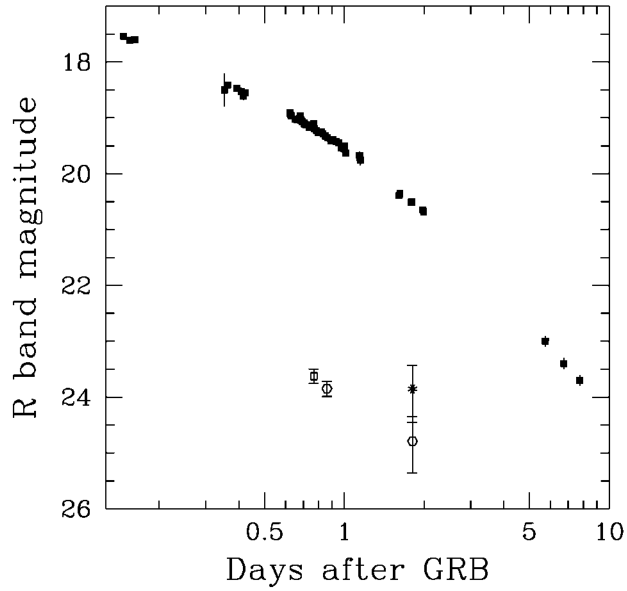

FIG. 2.—Light curve of GRB 990510 in *R*. Filled symbols give the total flux (Axelrod et al. 1999; Galama et al. 1999; Stanek et al. 1999; Vreeswijk et al. 1999a; Covino et al. 1999b, 1999c; Bloom et al. 1999; Lazzati et al. 1999; Marconi et al. 1999a, 1999b) and show the break in the decay at about 1.5 days. Open symbols give the polarized flux in *R*, obtained by multiplying the total flux by the percentage polarization. (*Squares*) Polarization from Covino et al. 1999d; (*hexagons*) our data, aperture photometry; (*star*) our data, psf photometry (see text).

m Antu telescope (VLT-UT1) on 1999 May 11.228 UT and May 12.17 UT. The polarization optics consist of a phase retarder plate mosaic and a Wollaston prism. A mask producing 20″ wide parallel strips was used to avoid overlap of the ordinary and extraordinary components of incident light. The CCD has 2k × 2k pixels of 0″.2 size. Each observation consisted of three Bessel R 10 minute exposures centered on the position of the optical transient (Vreeswijk et al. 1999a). Each exposure was obtained at a different phase retarder angle; we used a half-wavelength plate for the determination of the linear polarization. We also measured the polarimetric standards BD −13°5073 and BD −12°5133 (Wagner & Szeifert 1999) on both nights. For BD −13°5073 we find $(P, \theta) = (4.90 \pm 0.08\%, 161°.6 \pm 0°.5)$, compared with $(P, \theta) = (4.61 \pm 0.03\%, 151°.0 \pm 0°.7)$ by Wagner & Szeifert, and for BD −12°5133 we find $(P, \theta) = (5.07 \pm 0.13\%, 155°.7 \pm 0°.7)$, compared with $(P, \theta) = (4.33 \pm 0.03\%, 148°.0 \pm 0°.7)$. Since the standard values were measured in *B* band (T. Szeifert 1999, private communication), and *P* is chromatic, we regard the agreement as satisfactory. θ is hardly color-dependent, so the mean offset between the standards and our measured values of 9°.2 ± 1°.5 is real; all values quoted for the OT below are corrected for this amount of instrumental polarization. The typical seeing on May 11 and May 12 was 1″.0 and 2″.5, respectively. Details of the observations are given in Table 1.

The CCD frames were bias subtracted and flat fielded with the NOAO IRAF package in a standard way. The linear polarizations and the polarization angles of the optical transient and 23 field stars were calculated from each of the images using standard equations (Ramaprakash 1998).[11] We determined the Stokes parameters *Q* and *U* of the optical transient relative to these field stars, which corrects for possible instrumental and (local) interstellar polarization. No systematic variations of the field star polarizations with position on the CCD or magnitude were found. We therefore reference the OT Stokes parameters to the mean of the field stars, making the OT photometry dominate the error in the OT polarization measurement.

On May 11 we measure $\bar{Q} = (1.05 \pm 0.04)\%$, $\bar{U} = (-0.68 \pm 0.03)\%$ for the weighted mean Stokes parameters of the field stars (using aperture photometry). Correcting the measured $Q = (-0.28 \pm 0.18)\%$ and $U = (-1.52 \pm 0.26)\%$ of the OT with these numbers we find $Q_{\mathrm{OT}} = (-1.33 \pm 0.18)\%$, $U_{\mathrm{OT}} = (-0.84 \pm 0.26)\%$, corresponding to a linear polarization of $(1.6 \pm 0.2)\%$ at a position angle $\theta = 98° \pm 5°$. Gaussian PSF-fitting photometry was also performed on the OT and field stars using the DAOPHOT II package (Stetson 1987) and the *ALLSTAR* procedure in MIDAS. Combined with an alternative polarization analysis method (di Serego Alighieri 1997), we find $P = (1.6 \pm 0.2)\%$ and $\theta = 96° \pm 4°$, in good agreement with the aperture result.

Covino et al. (1999d) found that on May 11 (∼2 hr before our observations) the afterglow of GRB 990510 showed linear polarization of $(1.7 \pm 0.2)\%$ with $\theta = 101° \pm 3°$ (corrected from their preliminary report; S. Covino 1999, private communication, and Covino et al. 1999d). So in 2 hr, the polarization shows no evidence of change.

On May 12 the optical transient was 1.2 mag fainter ($R = 20.65$), and the observing conditions were much worse: over-

TABLE 1
LOG OF THE OBSERVATIONS

UT Date (1999 May)	Object	Angle (deg)	Exposure (s)	Seeing (arcsec)
11.223 ………	OT	0	600	1.3
11.231 ………	OT	22.5	600	1.3
11.239 ………	OT	45	600	1.4
11.406 ………	BD −13°5073	…	0.25	0.9
11.425 ………	BD −12°5133	…	0.25	1.0
12.168 ………	OT	0	600	2.6
12.175 ………	OT	22.5	600	2.6
12.183 ………	OT	45	600	2.6
12.239 ………	BD −12°5133	…	0.25	2.5
12.249 ………	BD −13°5073	…	0.25	2.5

NOTES.—The observations were performed with the 8.2 m Antu telescope, in standard resolution (0″.2 pixel^{-1}). "Angle" is the retarder angle, for each standard observation all angles were done (0, 22.5, 45, 67.5).

[11] See http://www.iucaa.ernet.in/˜anr/thesis.html.

head cirrus and a seeing of 2.″5. We applied the same procedure to the May 12 data, except that we used a smaller aperture and a fixed position of the OT (from the previous data) to minimize the contribution from a star 4″ away. We find for the comparison stars $Q = (1.06 \pm 0.04)\%$ and $U = (-0.38 \pm 0.04)\%$. Correcting the measured $Q = (0.1 \pm 0.9)\%$ and $U = (-2.0 \pm 1.2)\%$ we find $Q_{\rm OT} = (-1.0 \pm 0.9)\%$, $U_{\rm OT} = (-1.6 \pm 1.2)\%$. Since U and Q are determined from small differences in very high signal-to-noise detections of the OT, their errors will be approximately normally distributed. We therefore evaluated the mean value and 68% confidence interval for P and θ by Monte Carlo drawing many realizations of U and Q, computing P and θ for each, and inspecting the resulting distributions of P and θ. The result is that $P = (2.2^{+1.1}_{-0.9})\%$ and $\theta = 112^{+17°}_{-15°}$. This gives the impression that $P = 0$ is fairly well excluded. However, the simulations show that if we had measured an unpolarized source with the same precision in U and Q we would have had an 11% chance of measuring $P > 2.2\%$, so our detection is not very secure. Using PSF photometry, we find for this data set $Q_{\rm OT} = (-2.5 \pm 2.6)\%$ and $U_{\rm OT} = (-3.6 \pm 2.6)\%$, consistent with the aperture values, and resulting in $P = (5.2^{+2.5}_{-2.2})\%$ and $\theta = 99^{+19°}_{-16°}$ (and a 12% chance probability). The larger error is mostly due to the poorer seeing in the presence of a nearby star. This leads to some problems in the measurement that are not readily quantified as a random error, so we consider our measurement on night 2 as tentative. The polarized flux is plotted in Figure 2, along with the R-band light curve of the OT.

3. ORIGIN AND IMPLICATIONS OF THE POLARIZATION

Some (constant) polarization in the afterglow could be generated by dust scattering by the host's interstellar medium. For dust scattering to polarize the light even by a few percent, at least that fraction of the light must have been scattered. This requires a path length of many parsecs, which would cause a time delay of months between the (scattered) polarized light and the direct light, and thus could not cause polarization within a day of the GRB trigger. Electron scattering in the GRB itself could also lead to some polarization, as was seen, e.g., in SN1998bw and attributed to asymmetries in the photosphere (Kay et al. 1998). The degree of polarization could never be more than the electron scattering optical depth, however, which is typically never more than 10^{-6} after a day or so.

Intrinsic polarization is expected from any synchrotron source: $P_{\rm max} \sim 60\%$ is normal from an emitting region with one direction of the magnetic field. However, the net polarization from an unresolved source will still be small if the direction of the polarization averages out. There are two possible reasons why the polarization might average out to nearly zero: highly tangled magnetic fields and very highly symmetric field geometries. We now examine the consequences of both for our measurements and their interpretation.

The magnetic field could be highly tangled if it is generated by some form of turbulence. The source then consists of N patches within which the field has a single coherent direction, but no correlation between the patches. In that case, we expect a net polarization of order $P_{\rm max}/\sqrt{N}$. Gruzinov & Waxman (1999) considered a turbulently generated magnetic field, which has such a small scale that it would not likely leave a net polarization. However, they suggested that the coherence length of the field might grow, and the net polarization could be a few to 10 %. Loeb & Perna (1998) suggested that microlensing might amplify a few cells briefly, making the net polarization comparable to the value for a single cell for a short time.

A more ordered field was discussed by Medvedev & Loeb (1999), who consider the generation of a magnetic field parallel to the shock front. Due to aberration, it would be parallel to the ringlike image that the afterglow presents at late times (Waxman 1997b; Panaitescu & Mészáros 1998; Sari 1998), causing a radial polarization. The mean polarization of the image would still be zero for a spherical blast wave, due to averaging over the unresolved ring. Medvedev & Loeb (1999) suggest that interstellar scintillation will cause polarization by selectively magnifying part of the source; however, this scintillation only occurs at radio wavelengths, so it cannot explain the optical polarization.

Some asymmetry in the source results in significant net polarization (Gruzinov 1999). There are good indications of asymmetry in GRB 990510: the light curve in optical steepens after about 1.5 days in a wavelength-independent manner (Stanek et al. 1999; Harrison et al. 1999; Fig. 2). Such a steepening may indicate beaming: in a jetlike burst with opening angle θ, the light curve steepens when the Lorentz factor of the jet goes from $\Gamma > \theta^{-1}$ to $\Gamma < \theta^{-1}$ (Rhoads 1999; Mészáros & Rees 1999). Let our line of sight be offset somewhat from the jet axis. As long as $\Gamma \gg \theta^{-1}$ we cannot distinguish jets from spherical blast waves, hence the polarization is zero by symmetry. As the jet slows down we see its edge, causing asymmetry and net polarization as the light curve steepens. The direction of the polarization is constant, because it is fixed by the geometry of the beam relative to our line of sight. At late times, the polarization will decrease again, because the emission opening angle becomes much bigger than our offset from the center of the beam, reducing the asymmetry. So for polarization due to jets, we expect the polarization be strongest near the time of the break in the light curve. Note that because the effect of an ordered field could add up over the source, as opposed to the random case, an ordered field need not be nearly as strong as the random field to dominate the net polarization.

The way to distinguish random- and ordered-field interpretations of the polarization, then, is to look at the behavior of the polarization angle. If it is constant, this argues in favor of an ordered field; if it varies, then the field is more likely to be random. Our data compared with the measurement of Covino et al. (1999d) show a constant polarization for 2 hr. Gruzinov & Waxman (1999) estimate that for the conditions on night 1, i.e., a polarization of 1.6% at 0.86 days since trigger, the variation timescale of the polarization for a random field should be about 0.25 days. This is sufficiently larger than the 2 hour interval in the data to make a random field consistent with the measured constancy. For N identical patches, each with an intrinsic polarization of 60%, we find that some 1100 patches will give an expectation value for the net polarization equal to what we measure. But the distribution of net polarizations is broad for any N, and the 68% likely range is $N = 240$–2600. If the measurement on night 2 is taken at face value, it means that the polarization angle is constant over 1.0 days, rather longer than the predicted coherence time, and thus that an ordered field is preferred over a turbulent one. Given the problems with those data, we would rather consider this tentative inference an illustration of what we can learn with present instrumentation, under slightly more favorable conditions.

4. CONCLUSIONS

We have measured significant polarization in the afterglow of GRB 990510, which was an unremarkable burst in its gross gamma-ray properties, but notable in optical for providing good evidence of beaming. 0.86 days after trigger, we find $P =$

(1.6 ± 0.2)%, and a day later we marginally detect polarization at a similar level. We conclude that the polarization is not due to interstellar or intrasource scattering and attribute it to the synchrotron radiation from the blast wave itself. The polarization is constant between our data and those taken 2 hr earlier by Covino et al. (1999), and the detection in the second night is not good enough to check its variation over a 1 day period. The data are consistent with both random fields and ordered field as sources of the polarized flux. For a random field, we model the source as consisting of a number of independent patches, identical in everything but orientation of the field. We then find that 240–2600 patches are needed to bring the net polarization down from its intrinsic value of 60% in each patch to our measured 1.6%. We also show that future studies of polarization variations can provide further information about the structure of the magnetic field, especially about the presence of an ordered component.

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