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## GRB 990712: FIRST INDICATION OF POLARIZATION VARIABILITY IN A GAMMA-RAY BURST AFTERGLOW<sup>1</sup>

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### ABSTRACT

We report the detection of significant polarization in the optical afterglow of GRB 990712 on three instances: 0.44, 0.70, and 1.45 days after the gamma-ray burst, with  $(P, \theta)$  being  $(2.9\% \pm 0.4\%, 121^\circ \pm 3^\circ 5)$ ,  $(1.2\% \pm 0.4\%, 116^\circ 2 \pm 10^\circ 1)$ , and  $(2.2\% \pm 0.7\%, 139^\circ 2 \pm 10^\circ 4)$ , respectively. The polarization is intrinsic to the afterglow. The degree of polarization is not constant and is smallest at the second measurement. The polarization angle does not vary significantly during these observations. We find that none of the existing models predict such polarization variations at a constant polarization angle; we suggest ways in which these models might be modified to accommodate the observed behavior of this afterglow.

*Subject headings:* gamma rays: bursts — polarization — radiation mechanisms: nonthermal — turbulence

### 1. INTRODUCTION

The radiation from gamma-ray burst (GRB) afterglows has been hypothesized from early on to be synchrotron emission from relativistic electrons (e.g., Rees & Mészáros 1998; Mészáros & Rees 1997). The observation of broadband afterglow spectra (Galama et al. 1998; Bloom et al. 1998) and the fact that the temporal evolution of the flux from radio to X-ray wavelengths often follows simple model predictions support this theoretical framework (Sari 2000; Piran 1999; van Paradijs, Kouveliotou, & Wijers 2000). Since synchrotron radiation is intrinsically highly polarized (with degrees of linear polarization up to 60%–70%; Rybicki & Lightman 1979), it would be natural to expect polarization in afterglow emission.

The first attempt to measure optical polarization of afterglow emission for GRB 990123 set an upper limit of 2.3% (Hjorth et al. 1999). The next attempts to measure polarization were successful, leading to the detection of polarization of 1.7% in the afterglow of GRB 990510 (Covino et al. 1999; Wijers et al. 1999). Such low percentages of polarization are somewhat surprising, and models have been mostly concerned with trying to explain the *depolarization* of gamma-ray bursts. Two principal hypotheses have been advanced. First, the emission from the GRB is so highly ordered that the symmetry of the source causes the net polarization to average out to zero, even though it is locally high everywhere (Medvedev & Loeb 1999). Second, the emitting

medium is very random on small scales, and the emission we see is composed of many uncorrelated polarization patches so that the mean is again close to zero (Gruzinov & Waxman 1999). Both these models easily obtain the low polarization levels observed, and they differ only on the circumstances under which polarization may be observed and what its temporal evolution should be. In the afterglow of GRB 990510, the close spacing of the early observations and the large measurement errors later on precluded any strong conclusions about preferred models.

GRB 990712 was detected with the *BeppoSAX* Gamma-Ray Burst Monitor and Wide Field Cameras Unit 2 on 1999 July 12.69655 UT (Heise 1999). The first optical follow-up observations started 4.16 hr after the burst, leading to the discovery of an optical transient (OT) of magnitude  $R_{OT} \approx 19.4$  (Bakos et al. 1999). The light curve of the OT is quickly dominated by the light of its fairly bright host galaxy, with  $R_H \approx 22$ .

A detailed description of the photometry of the OT is given by Sahu et al. (2000) and Hjorth et al. (2000). Galama et al. (1999) determined a redshift of  $z = 0.430 \pm 0.005$  for the OT. Spectroscopic observations of GRB 990712 are reported in Hjorth et al. (2000) and Vreeswijk et al. (2001).

The outline of this paper is as follows. In § 2 we describe the observations and data reduction. We analyze the results in § 3 and discuss their significance for existing models in § 4, as well as possible modifications to those models. Finally, we summarize our findings in § 5.

### 2. OBSERVATIONS

Three epochs of observations were taken on July 13 and 14 with the Very Large Telescope (VLT) of the European Southern Observatory at Paranal, Chile, using VLT Unit Telescope 1 (Antu) and the focal reducer/low dispersion spectrograph (FORSl). Table 1 gives a log of observations. All images were taken with a Bessel *R*-band filter. In order to obtain the degree of linear polarization, a Wollaston prism and a half-wavelength, phase-retarder plate were used as polarization optics. The Wollaston prism separates the incident light into two components (an ordinary and an extraordinary component), where the half-wavelength plate

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TABLE 1  
LOG OF POLARIMETRIC OBSERVATIONS OF THE GRB 990712 AFTERGLOW

UT Date <sup>a</sup> (1999)	Days (After the Burst)	seeing <sup>b</sup> (arcsec)	$P$ (%)	$\theta$ (deg)	$P_{av}$ (%)	$\theta_{av}$ (deg)
Jul 13.1402	0.4436	1.0	$2.9 \pm 0.4$	$121.1 \pm 3.5$	$1.89 \pm 0.02$	$175.5 \pm 0.3$
Jul 13.3936	0.6971	0.8	$1.2 \pm 0.4$	$116.2 \pm 10.1$	$2.06 \pm 0.02$	$176.3 \pm 0.2$
Jul 14.1415	1.4450	1.1	$2.2 \pm 0.7$	$139.2 \pm 10.4$	$1.91 \pm 0.02$	$175.4 \pm 0.2$

NOTE.—Log of the polarimetric observations of the GRB 990712 afterglow with ESO VLT Antu (UT1) and FORS1. The exposure time for epochs 1 and 2 was  $4 \times 300$  s and for epoch 3,  $4 \times 450$  s.  $P_{av}$  and  $\theta_{av}$  denote the average values of the field stars (not corrected for instrumental and interstellar polarization).

<sup>a</sup> Mid-exposure date.

<sup>b</sup> The seeing varied somewhat during the measurements; the values listed here are averages.

is used to determine which Stokes parameter is measured ( $U$  or  $Q$ ). A mask producing  $22''$  wide parallel strips was used to avoid overlap of the ordinary and extraordinary rays. Each observation consisted of four exposures centered on the position of the OT, with the phase-retarder plate rotated by  $22.5^\circ$  between successive exposures.

The data were reduced in a standard way with the NOAO IRAF<sup>11</sup> package *ccdred*, first bias-subtracted and then flat-fielded. The fluxes of the point sources in the field were determined using aperture photometry, with an aperture radius of 1 FWHM of the point-spread function.

To correct for any instrumental or local interstellar polarization, we measure the polarization of the OT relative to 21 field stars in the same image. We have plotted the Stokes parameters  $U$  and  $Q$  of both the field stars and the OT in Figure 1. The OT clearly stands out, having the lowest  $U$ -value. We verified that there are no systematic variations of  $U$  and  $Q$  of the field stars with magnitude or position on the CCD; therefore we can correct the polarization parameters of the OT for foreground effects by subtracting the mean  $U$ - and  $Q$ - values of the field stars from those of the OT.

### 3. RESULTS

To derive the degree of linear polarization, we first calculate  $Q$  and  $U$  using standard equations (see, e.g., Ramaprakash 1998), both for the OT and for the field stars. We then subtract the average  $Q$ - and  $U$ - values of the field stars from those of the OT. The resulting  $Q$  and  $U$  are used to calculate the degree and the position angle of the linear polarization. We have also used a different method (see, e.g., di Serego Alighieri 1997), which within the errors leads to the same results. This method uses the relation  $S(\phi) = P \cos 2(\theta - \phi)$ , with the parameter  $S(\phi)$  being a measure for the ratio between the two components of the incident light, separated by the Wollaston prism, and  $\phi$  the corresponding angle of the prism. Figure 2 gives a cosine fit to the data of the first epoch.

In Figure 3 we have plotted the polarized flux together with the  $R$ - and  $V$ -band light curve. The plot clearly shows the change in polarization, while the light curve exhibits a smooth decline. There is also no indication of a change in the ( $V-R$ ) color of the afterglow.

We assume that the degree of linear polarization and the position angle are constant during the observation. One

might wonder if the decaying intensity of the source would affect the polarization. Since the Wollaston prism separates the incident light into two components, these two intensities change simultaneously and in the same way. Both  $Q$  and  $U$  are calculated from the ratio of these two components and should not be affected by variation in the intensity of the source.

Both the degree of linear polarization and the position angle versus the time since the burst are plotted in Figure 4. We see that the polarization percentage,  $P$ , decreases between 0.44 and 0.7 days after the burst, with  $3.2 \sigma$  significance. Then at 1.45 days,  $P$  is greater again, but since the difference between the last and middle observation is only  $1.5 \sigma$ , we cannot be too sure about this rise of  $P$ .

In the case that the degree of polarization were constant, with a mean value of  $2.1\% \pm 0.3\%$ , the  $P$ -value at epoch 1 would be just within  $3 \sigma$  above the mean, while for epoch 2 it would be just  $3 \sigma$  below it. The variability could then be caused by a systematic error. To check this, we have compared the polarization values of the separate field stars at each of the three epochs with the mean value. We have not found any evidence for such a systematic error and conclude that the observed variability in the polarization is most likely intrinsic to the source.

Therefore, we think that we have clearly detected, for the first time, variation in the polarization of a GRB afterglow, which could either be a decline that is initially steep and then levels off, or a decline followed by a rise. The polarization angle, at the same time, never changed by more than  $1 \sigma$  from one observation to the next.

As argued for the case of GRB 990510, polarization in a rapidly varying source is unlikely to be induced by interstellar scattering (Wijers et al. 1999). In the present case, where the polarization itself varies, this is even more strongly so: stars with polarization induced by interstellar scattering are favorite polarization standards, because their degree of polarization is very constant.

### 4. DISCUSSION

Intrinsic polarization from a synchrotron source can be as large as  $P_{max} \sim 60\% - 70\%$  (Rybicki & Lightman 1979) if the magnetic field is oriented in one direction. However, for an unresolved source, the net polarization will be small if the different directions of the polarization average out. This could be caused by highly tangled magnetic fields or by a very simple symmetry in the large-scale field pattern.

If the magnetic field in the GRB afterglow is highly tangled, we can think of it as a source consisting of  $N$  patches (Gruzinov & Waxman 1999). The net polarization resulting from the source will then be of order  $P_{max}/\sqrt{N}$ .

<sup>11</sup> IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

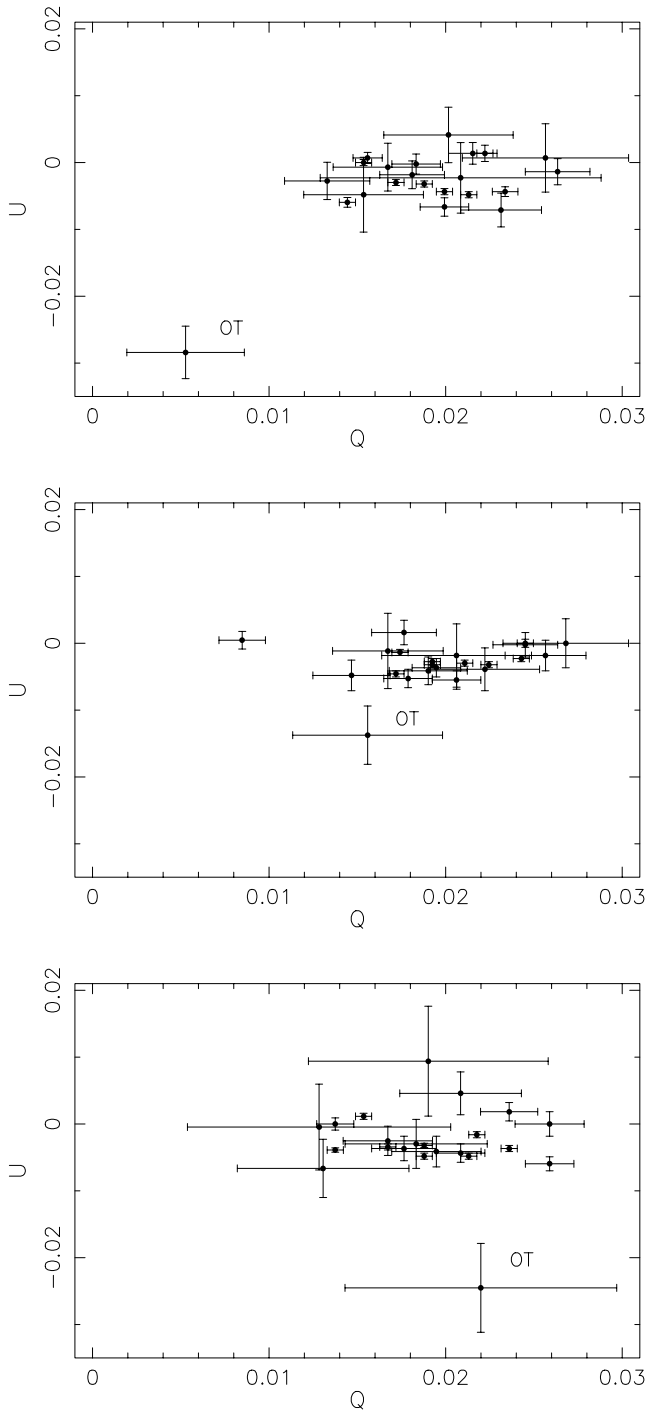


FIG. 1.— $(Q, U)$  plot of the stars in the field after instrumental correction, for epochs 1, 2, and 3 (*top*, *middle*, and *bottom*, respectively). The OT clearly stands out with respect to the other stars in the field, indicating that it has a considerable intrinsic amount of polarization.  $(Q, U)$  averages of the field stars for the three epochs are  $(0.0194 \pm 0.0004, -0.0021 \pm 0.0005)$ ,  $(0.0200 \pm 0.0003, -0.0024 \pm 0.0004)$ , and  $(0.0190 \pm 0.0005, -0.0019 \pm 0.0004)$ , respectively, showing that there is no significant change in the interstellar and instrumental polarization.

The maximum degree of linear polarization observed (at epoch 1) requires a magnetic field divided up into  $\sim 400$  patches. For the second epoch, we see a decrease in the degree of linear polarization (with  $\theta$  being constant), which would lead to  $\sim 2500$  patches 6 hr later. We note, however, that in that case the polarization angle should also vary by

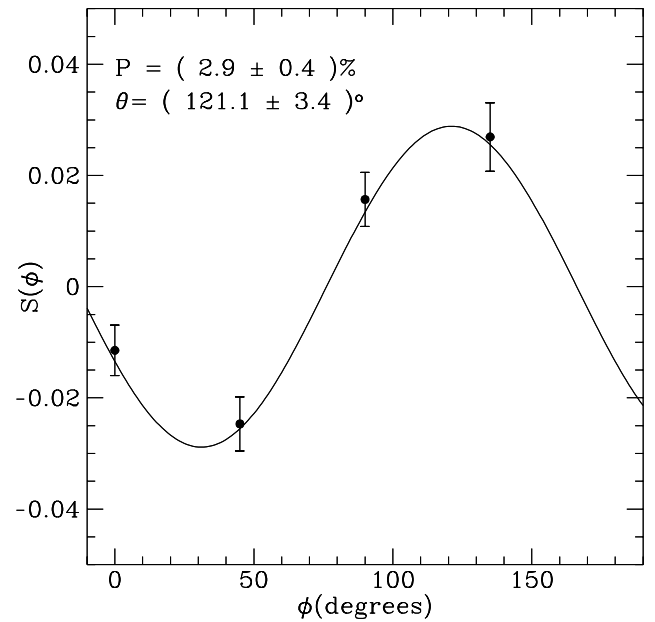


FIG. 2.—Parameter  $S(\phi)$  at four different position angles  $\phi$ . The data are fit with a cosine function. The amplitude of the fit corresponds to the degree of linear polarization, and its maximum gives the position angle of the polarization.

the same percentage, implying that we expect a change of order 1 radian between the first and second epoch in a tangled-field model. However, we see no significant change in the polarization angle, with a 1 radian variation ruled out at the  $4\sigma$  level, making this model unlikely.

A symmetric model for the polarization cancellation arises when the magnetic field is ordered perpendicular to or parallel to the ring of emission we see from the afterglow at any given time (Waxman 1997; Panaitescu & Mészáros 1998; Sari 1998). This could naturally arise in some instabilities that generate magnetic fields (Medvedev & Loeb 1999; Gruzinov 1999). In a spherically symmetric fireball, the polarization would then be exactly zero, so an extra effect is needed to break the symmetry and get a net polarization. One possibility is that some turbulence induces

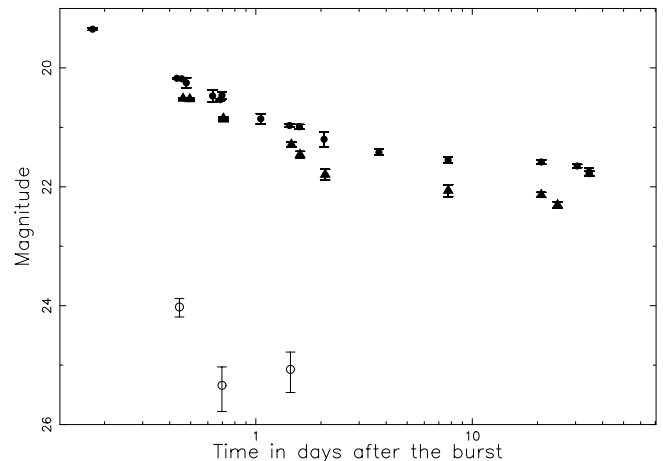


FIG. 3.—Light curve of GRB 990712.  $V$ - and  $R$ -band data (*filled circles* and *triangles*, respectively) are from Sahu et al. (2000). The open circles indicate the polarization magnitudes.

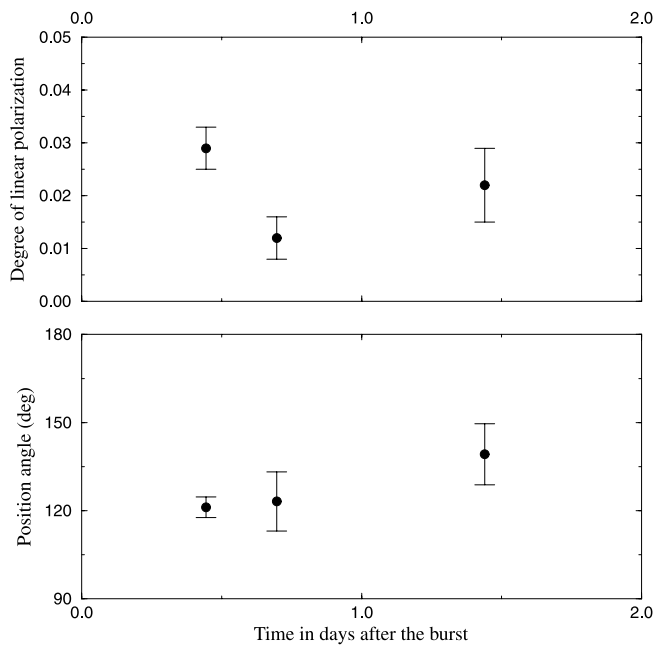


FIG. 4.—Variation of  $P$  and  $\theta$  during the three observations

brightness variations, thus weighting some polarization directions more, or that an external effect such as scintillation or microlensing might enhance the emission from some parts of the ring (Loeb & Perna 1998; Medvedev & Loeb 1999). However, any polarization variations from such a mechanism would be expected to be in both degree and angle, contrary to what we see.

Another symmetric model is a jet. As explained in Ghisellini (1999) and Sari (1999), a collimated burst will naturally exhibit polarization, up to 20%, around the time when the light curve steepens. However, we have no evidence of such a break in the light curve of GRB 990712. Also, in a jet model, the degree of polarization varies without change of the polarization angle, until the polarization goes through zero and the angle suddenly changes by  $90^\circ$ . Therefore, one could, in principle, have a situation of varying polarization without variation of the angle, as we see here in a jet model. However, the sharp drop from epoch 1 to 2 followed by little change to epoch 3 seems hard to get without a zero transit around epoch 2, if we compare Figure 4 with the theoretical curves of Sari (1999) and Ghisellini (1999). So, at least for the simple models published thus far, our data cannot be explained by a beamed jet.

In summary, current models of polarization variations predict significant changes of the polarization angle along with variations of the degree of polarization or, in the case

of a jet model, the degree of polarization to be around a peak for a constant polarization angle. Since we do not observe such a combination of the polarization angle and degree of polarization in the afterglow of GRB 990712, we conclude that no current model adequately explains our data.

## 5. CONCLUSIONS

We have observed significant polarization for the afterglow of GRB 990712 during three epochs—from 0.4 to 1.5 days after the burst. The polarization percentage varies by  $3.2\sigma$  from 3.0% at the first epoch to 1.2% at the second, while the polarization angle remains essentially constant. We show that neither tangled-field nor broken-symmetry models of the polarization of afterglows can explain this constancy of the polarization angle while the degree of polarization goes up and down. It appears that the afterglow polarization has some amount of memory for direction while varying in strength. One might speculate that this is telling us something about the formation of the magnetic field in the shocked afterglow material. Possibly, this field is grown from a seed field that is embedded in the swept-up ambient material. While the amount of amplification and field strength may vary with time and give rise to variable polarization, the direction of the seed may remain imprinted on the amplified field, and thus the polarization angle may be relatively constant. (Few-day-old afterglows are  $10^{16}$ – $10^{17}$  cm in size, on which scale interstellar magnetic fields can be coherent.)

The results show that in order to further test models, we need more measurements per burst to better sample the polarization behavior and possibly over a larger range of time. Since the measurements require photometry with a signal-to-noise ratio of 300 or so, they already stretch the capabilities of the VLT after 1.5–2 days, so it is unlikely that we shall be able to do measurements of the polarization at later times. However, it may be possible to extend the time interval of polarization measurements to earlier times. In a power-law process like GRB afterglows, it may be as profitable to move the first observing time forward from 0.4 to 0.2 days as it is to extend the last one from 2 to 4 days.

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