

*Letter to the Editor***GRB 990510: linearly polarized radiation from a fireball\***

**Stefano Covino<sup>1</sup>, Davide Lazzati<sup>1,2</sup>, Gabriele Ghisellini<sup>1</sup>, Paolo Saracco<sup>1</sup>, Sergio Campana<sup>1</sup>, Guido Chincarini<sup>1,2</sup>, Sperello Di Serego<sup>3</sup>, Andrea Cimatti<sup>3</sup>, Leonardo Vanzi<sup>4</sup>, Luca Pasquini<sup>4</sup>, Francesco Haardt<sup>5</sup>, Gian Luca Israel<sup>6</sup>, Luigi Stella<sup>6</sup>, and Mario Vietri<sup>7</sup>**

<sup>1</sup> Osservatorio Astronomico di Brera, Via Bianchi 46, I-23807 Merate (Lc), Italy

<sup>2</sup> Dipartimento di Fisica, Università degli Studi di Milano, Via Celoria 16, I-20133 Milano, Italy

<sup>3</sup> Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125 Firenze, Italy

<sup>4</sup> European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-85748 Garching, Germany

<sup>5</sup> Università dell'Insubria, via Lucini 3, I-22100 Como, Italy

<sup>6</sup> Osservatorio Astronomico di Roma, via Frascati 33, I-00040 Monteporzio Catone, Roma, Italy

<sup>7</sup> Università di Roma III, via della Vasca Navale 84, I-00147 Roma, Italy

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**Abstract.** Models for gamma-ray burst afterglows envisage an hyper-relativistic fireball that is decelerated in the ambient medium around the explosion site. This interaction produces a shock wave which amplifies the magnetic field and accelerates electrons to relativistic energies, setting the conditions for an efficient production of synchrotron photons. If produced in a region of large-scale ordered magnetic field, synchrotron radiation can be highly polarized. The optical transient associated with GRB 990510 was observed  $\sim 18.5$  hr after the event and linear polarization in the  $R$  band was measured at a level of  $1.7 \pm 0.2\%$ . This is the first detection of linear polarization in the optical afterglow of a gamma-ray burst. We exclude that this polarization is due to dust in the interstellar material, either in our Galaxy or in the host galaxy of the gamma-ray burst. These results provide important new evidence in favor of the synchrotron origin of the afterglow emission, and constrains the geometry of the fireball and/or magnetic field lines.

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

## 1. Introduction

GRB 990510 was detected by BATSE on-board the Compton Gamma Ray Observatory and by the *BeppoSAX* Gamma Ray Burst Monitor and Wide Field Camera on 1999 May 10.36743 UT (Kippen 1999, Amati et al. 1999, Dadina et al. 1999). Its fluence ( $2.5 \times 10^{-5}$  erg cm $^{-2}$  above 20 keV) was relatively high (Kippen 1999). Follow up optical observations started  $\sim 3.5$  hr

later and revealed an  $R \simeq 17.5$  (Axelrod et al. 1999) optical transient, OT (Vreeswijk et al. 1999a), at the coordinates (J2000)  $\alpha = 13^{\text{h}}38^{\text{m}}07.11^{\text{s}}$ ,  $\delta = -80^{\circ}29'48.2''$  (Hjorth et al. 1999b) (galactic coordinates  $l^{\text{II}} = 304.942$ ,  $b^{\text{II}} = -17.8035$ ). Fig. 1 shows the Digital Sky Survey II image of the field of GRB 990510, together with the European Southern Observatory (ESO) Very Large Telescope (VLT) image we obtained (see below): the OT is clearly visible in the latter.

The OT showed initially a fairly slow flux decay  $F_{\nu} \propto t^{-0.85}$  (Galama et al. 1999), which gradually steepened,  $F_{\nu} \propto t^{-1.3}$  after  $\sim 1$  d (Stanek et al. 1999a),  $F_{\nu} \propto t^{-1.8}$  after  $\sim 4$  d (Pietrzynski & Udalski 1999, Bloom et al. 1999),  $F_{\nu} \propto t^{-2.5}$  after  $\sim 5$  d (Marconi et al. 1999a, 1999b)). Vreeswijk et al. (1999b) detected Fe II and Mg II absorption lines in the optical spectrum of the afterglow. This provides a lower limit of  $z = 1.619 \pm 0.002$  to the redshift, and a  $\gamma$ -ray energy of  $> 10^{53}$  erg, in the case of isotropic emission.

Polarization is one of the clearest signatures of synchrotron radiation, if this is produced by electrons gyrating in a magnetic field that is at least in part ordered. Polarization measurements can provide a crucial test of the synchrotron shock model (Mészáros & Rees 1997). An earlier attempt to measure the linear polarization of the optical afterglow of GRB 990123 yielded only an upper limit (Hjorth et al. 1999a) of  $\sim 2.3\%$ .

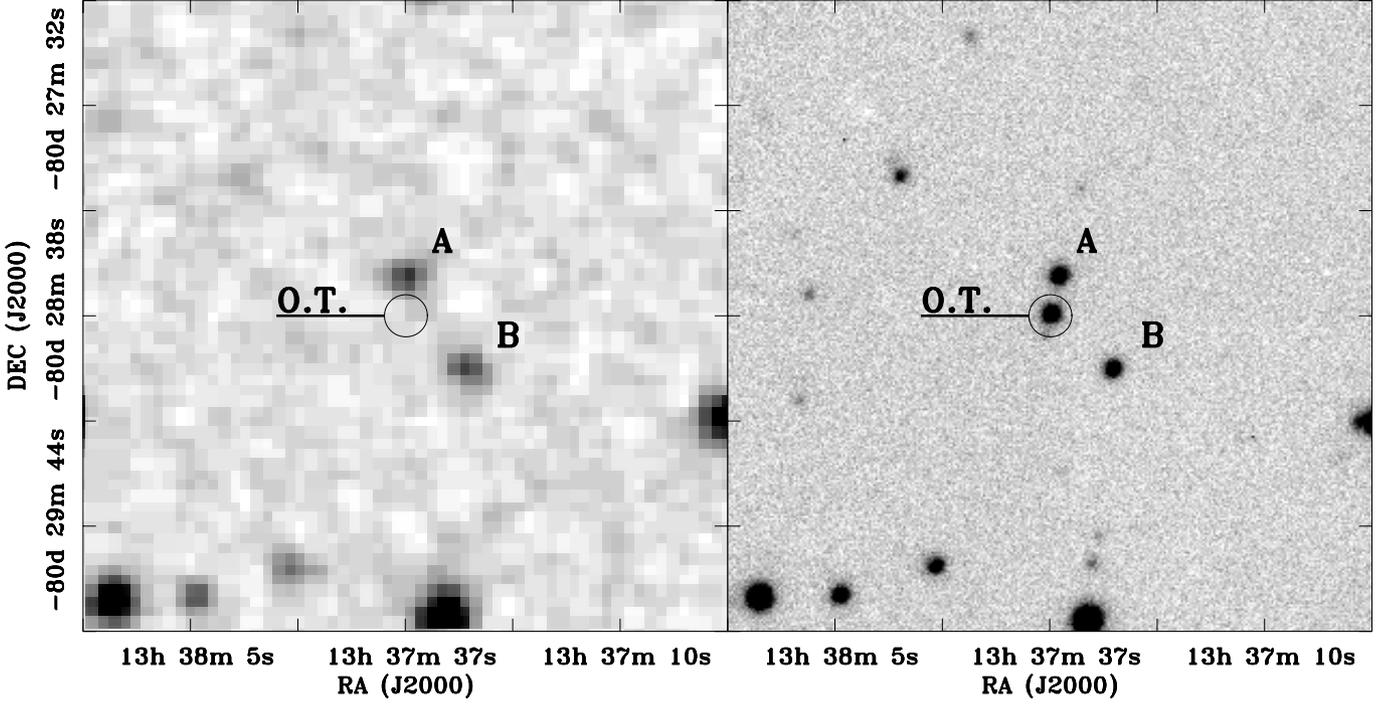
## 2. Observations

Our observations of GRB 990510 were obtained at ESO's VLT-Antu (UT1), equipped with the Focal Reducer/low dispersion Spectrometer (FORS) and Bessel filter  $R$ . The OT associated with GRB 990510 was observed  $\sim 18.5$  hr after the burst, when the  $R$ -band magnitude was  $\sim 19.1$ . Observations were performed in standard resolution mode with a scale of  $0.2''/\text{pixel}$ ; the seeing was  $\sim 1.2''$ . The observation log is reported in Table 1.

Send offprint requests to: S. Covino

\* Based on ESO VLT-Antu (UT1) observations (63.H-0233). Raw data are available upon request.

Correspondence to: covino@merate.mi.astro.it



**Fig. 1.** *Left:* The Digital Sky Survey II image ( $1' \times 1'$ ) of the field of GRB 990510. The position of the optical transient is indicated by the circle. *Right:* The VLT image of the same field shows the optical transient at the magnitude of  $R \sim 19$ , about 18 hours after the burst.

**Table 1.** Observation log for the polarimetric observation of the GRB 990510 field.

Starting time UT, 1999/05/11	Exposure sec	Angle degrees	filter
02:48	600	00.0	R
02:59	600	22.5	R
03:10	600	45.0	R
03:21	600	67.5	R

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  $\phi$  and  $\phi + 90^\circ$ .

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 points in Fig. 2 (see Eq. 1). This technique removes any difference between the two optical paths (ordinary and extraordinary ray) and the polarization component introduced by galactic interstellar grains along the line of sight. Moreover, being based on relative photometry in simultaneous images, our measurements are insensitive to intrinsic variations in the optical transient flux ( $\sim 0.03$  magnitudes during the time span of our observations). With the same procedure, we observed also two polarimetric standard stars, BD-135073 and BD-125133, in order to fix the offset between the polarization and the instrumental angles.

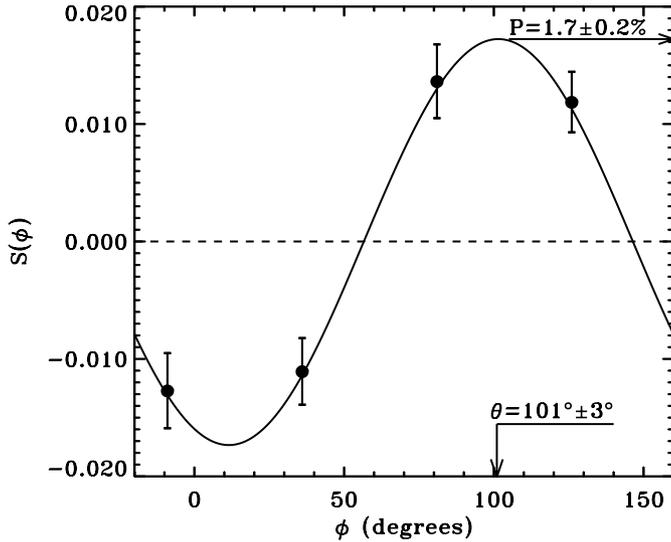
The data reduction was carried out with the ESO-MIDAS (version 97NOV) system. After bias subtraction, non-uniformities were corrected using flat-fields obtained with the Wollaston prism. The flux of each point source in the field of view was derived by means of both aperture and profile fitting photometry 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 order to evaluate the parameters describing the linear polarization of the objects, we compute, for each instrumental position angle  $\phi$ , the quantity:

$$S(\phi) = \frac{\frac{I(\phi)/I(\phi+90^\circ)}{\langle I_u(\phi)/I_u(\phi+90^\circ) \rangle} - 1}{\frac{I(\phi)/I(\phi+90^\circ)}{\langle I_u(\phi)/I_u(\phi+90^\circ) \rangle} + 1} \quad (1)$$

where  $I(\phi)$  and  $I(\phi + 90^\circ)$  are the intensities of the object measured in the two beams produced by the Wollaston prism, and  $\langle I_u(\phi)/I_u(\phi + 90^\circ) \rangle$  are the average ratios of the intensities of the stars in the field. This corrects directly for the small instrumental polarization (and, at least in part, for the possible interstellar polarization). These field stars (see Fig. 3) have been selected over a range in magnitude ( $18 \leq R \leq 22$ ) to check for possible non-linearities. Since the interstellar polarization of any star in the field may be related to the patchy dust structure and/or to the star distance, we have verified that the result does not depend on which stars are chosen for the analysis. The parameter  $S(\phi)$  is related to the degree of linear polarization  $P$  and to the position angle of the electric field vector  $\vartheta$  by:

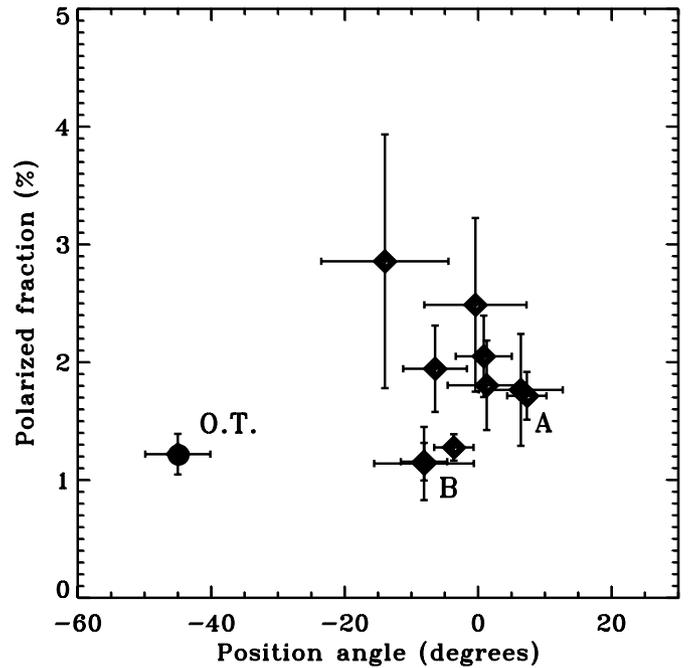
$$S(\phi) = P \cos 2(\vartheta - \phi). \quad (2)$$



**Fig. 2.** Our polarization data taken at four different position angles  $\phi$  are fitted with a cosine curve. The amplitude of this curve corresponds to the degree of linear polarization, and its maximum to the polarization position angle. Data are normalized to the average of the stars in the same field (see Eq. 1).

$P$  and  $\vartheta$  are evaluated by fitting a cosine curve to the observed values of  $S(\phi)$ . The derived linear polarization of the OT of GRB 990510 is  $P = (1.7 \pm 0.2)\%$  ( $1\sigma$  error), at a position angle of  $\vartheta = 101^\circ \pm 3^\circ$ <sup>1</sup>. The errors for the polarization level and position angle are computed propagating the photon noise of the observations and the contribution of the normalization to the stars in the field and of the calibration of the position angle. The latter quantities, however, amounts to only a minor fraction of the quoted  $1\sigma$  uncertainties. Fig. 2 shows the data points and the best fit  $\cos \phi$  curve. The statistical significance of this measurement is very high. A potential problem is represented by a “spurious” polarization introduced by dust grains interposed along the line of sight, which may be preferentially aligned in one direction. Stanek et al. (1999b), using dust infrared emission maps (Schlegel et al. 1998), reported a substantial Galactic absorption ( $E_{B-V} \simeq 0.20$ ) in the direction of GRB 990510. The maps by Dickey & Lockman (1990) and by Burstein & Heiles (1982) give instead a somewhat lower value,  $E_{B-V} \simeq 0.17$  and  $\simeq 0.11$ , respectively. Applying an empirical relation (Hiltner 1956, Serkowski et al. 1975) this polarization can amount to  $P_{\max} \leq 9.0 E_{B-V}$ , i.e.  $\sim 1$ –2%. These are only statistical estimates and large variations on the main trend may be expected. Then a fraction, or even all the polarization of the OT could be caused by the passage of its light through the galactic ISM. However the normalization of the OT measurements to the stars in the field already corrects for the average interstellar polarization of these stars, even if this does not necessarily account for all the effects of the galactic ISM along the line of sight to the OT (e.g. the ISM could be more distant than the stars, not inducing any polarization of their light). To check this

<sup>1</sup> Please, note that the position angle reported in IAUC 7172 is incorrect by  $90^\circ$



**Fig. 3.** The unnormalized degree of polarization vs the instrumental polarization position angle of the stars in the field and the optical transient. The optical transient clearly stands out ( $P = 1.2 \pm 0.2\%$ ). Stars A and B of Fig. 1 are also labelled.

possibility, we plot in Fig. 3 the degree of polarization vs. the instrumental position angle for each star and for the OT. All points in this figure have been derived avoiding to normalize with respect to other objects. It is apparent that, while the position angle of all stars are consistent with being the same (within 10 degrees), the OT clearly stands out. The polarization position angle of stars close to the OT differs by  $\sim 45^\circ$  from the position angle of the OT (see Fig. 3). This is contrary to what one would expect if the polarization of the OT were due to the galactic ISM. Indeed, the higher polarization level measured for the OT when normalized to the stars in the same field implies that the ISM actually *somewhat de-polarizes* the OT. We therefore conclude that the OT, even if contaminated by interstellar polarization, must be intrinsically polarized to give the observed orientation.

We can place tight limits on the amount of absorption, and hence the associated polarization, that could be produced by interstellar material in the host galaxy of GRB 990510. Assuming that the intrinsic spectrum is a power law ( $F_\nu \propto \nu^{-\alpha}$ ), we require that the fluxes measured simultaneously in the  $B$ ,  $V$ ,  $R$  and  $I$  band (Pietrzynski & Udalski 1999; Kaluzny et al. 1999; Hjorth et al. 1999b) lie on a power law curve. This strongly limits the amount of the local extinction, affecting the flux at rest-frame frequencies of  $\nu' = (1+z)\nu_{\text{obs}}$ , i.e. in the UV, where extinction is more severe. We find a maximum allowed value  $E_{B-V}^{\text{host}} \sim 0.02$ , corresponding to a maximum induced polarization level of  $\sim 0.2\%$ . Incidentally, the best fit power law is obtained for  $\alpha \sim 0.7$ , a galactic  $E_{B-V} = 0.16$  and  $E_{B-V}^{\text{host}} \sim 0$ . This value of  $\alpha$  matches the predictions of the standard model for the decaying afterglow flux (Mészáros & Rees 1997), which

gives  $F_\nu(t) \propto t^{-3\alpha/2}$ . For  $\alpha = 0.7$ , the expected flux decay is in agreement with that measured at the time of the observations.

### 3. Discussion

Relativistic fireball models do explain the main properties of GRBs and their afterglows (Rees & Mészáros 1992, Vietri 1997, Waxman 1997, Sari et al. 1998). Polarized optical synchrotron emission may be observable if: (i) the coherence length of the magnetic field in the fireball grows at a sizeable fraction of the speed of light (Gruzinov & Waxman 1999; Gruzinov 1999) or, (ii) the fireball is collimated (Hjorth et al. 1999a) (i.e. it is beamed). Therefore, measurements of optical polarization can provide constraints on the geometry of the emitting source.

Additional information come from the afterglow light curve which shows a gradual steepening in the bands  $V$ ,  $R$  and  $I$ , which was never observed before (Marconi et al. 1999a). The observed steepening is almost wavelength independent, thus excluding that it could be entirely caused by a curved spectrum shifting in time rigidly to lower frequencies, in which case we ought to see the highest frequencies steepening first. In addition, the  $V - R$  and  $R - I$  colors are changing very slowly during the evolution, indicating that the spectral slope is changing slowly with time. These information suggest that the fireball is collimated in a jet. The solid angle of the jet visible to the observer is limited to those regions making an angle smaller than  $1/\Gamma$  with the line of sight. As  $\Gamma$  decreases, the visible solid angle increases as  $1/\Gamma^2$ , until  $\Gamma = \Gamma_1 = 1/(\theta_j - \theta)$  (with  $\theta_j$  being the cone of semi-aperture angle and  $\theta$  the angle between the cone axis and the line of sight). When  $\Gamma = \Gamma_2 = 1/(\theta_j + \theta)$  the observed solid angle remains constant, since the entire jet is visible. For  $\Gamma$ -factors between  $\Gamma_1$  and  $\Gamma_2$  the observed solid angle increases somewhat slower than  $1/\Gamma^2$ . Since the flux at the earth is proportional to the observed solid angle, we have two well defined behaviors of the light curve, corresponding to  $\Gamma > \Gamma_1$  and  $\Gamma < \Gamma_2$ , and a transition period of gradual steepening in between. Photons produced in regions at an angle  $1/\Gamma$  with respect to the line of sight are emitted, in the comoving frame, at  $\sim 90^\circ$  from the velocity vector. A comoving observer at this angle can then see a compressed emitting region and a projected magnetic field structure with a preferred orientation. If the gradual steepening of the light curve is due to the mechanism just mentioned, we would observe only some regions at a viewing angle  $1/\Gamma$ , not all those we would see in axis-symmetric situation, and this asymmetry can be the cause of the observed linear polarization.

The above arguments suggest that we are observing, slightly off-axis, a collimated beam. If this is the case, we would have a link between the flux decay behavior, the presence of polarization, and the degree of collimation, opening a new perspective for measuring the intrinsic power of GRBs.

Deeper understanding of polarization in GRBs may come from future multi-filter observations and from spectropolarimetry. Frequency dependent polarization can in fact easily disentangle different components of polarization. In addition, variability in the degree of polarization and its position angle is expected in such fastly evolving sources: therefore repeated observations of the same afterglow will also be important.

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