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Polarimetric Constraints on the Optical Afterglow Emission from GRB 990123

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Polarization of the optical emission from GRB 990123 was measured on 24.17 January 1999 universal time (UT) with the Nordic Optical Telescope. An upper limit of 2.3% on the linear polarization was found. Accurate polarization measurements provide important clues to the blast wave geometry and magnetic field structure of gamma-ray bursts. The lack of detectable polarization for GRB 990123 indicates that the optical afterglow was produced by a blast wave of unknown geometry with an insignificant coherent magnetic field or by a beamed outflow at high Lorentz factor seen at a small viewing angle. Such a collimated jet would help solve the problem of energy release in this exceptionally luminous cosmological burst.

Optical afterglow, observed following nine γ-ray bursts (GRBs) over the past 2 years, is believed to be synchrotron radiation from an expanding ultrarelativistic blast wave (*1*). The exact source geometry and emission mechanism is unknown but can be constrained by accurate optical polarization measurements. Polarization may be expected if the emission is beamed or originates in a magnetic field produced by the blast wave with a coherence length growing at the speed of light.

GRB 990123 was a very bright GRB (*2*) accompanied by a $V \approx 9$ optical flash (*3*). The afterglow was the brightest ever recorded in x-rays (*2*) and sufficiently bright at optical wavelengths (*4*) to allow detailed ground-based observations (*5*, *6*). This led to constraints on its redshift $1.60 \leq z < 2$ (*6, 7*), making it the intrinsically most luminous GRB observed to date with an inferred isotropic energy release in γ rays alone of about $E_\gamma\, \pi/\Omega \sim 4 \times 10^{54}$ erg (*6*), comparable only to GRB 980329, if that burst occurred at $z \sim 5$ (*8*).

As soon as the location of the optical afterglow of GRB 990123 became visible at the 2.56-m Nordic Optical Telescope (NOT) on La Palma, The Canary Islands, observations designed to detect any polarization at the 10% level with high confidence were conducted. Polarimetric imaging observations were obtained with the Andalucia faint object spectrograph (ALFOSC) using two calcite blocks together with a red (R) broad-band filter (wavelength range: 5670 Å to 7150 Å). Each exposure gave two orientations of the polarization, 0° and 90°, or −45° and 45° (Table 1 and Fig. 1).

The linear polarization was computed from the derived fluxes in the four orientations. Assuming that no instrumental polarization or other systematic bias was present, the resulting linear polarization is 0.6 ± 1.4%. If the polarization is determined relative to the two stars present in the field of view (Fig. 1) a maximum of 1.2 ± 1.4% linear polarization is found. Under the assumption that the two stars are unpolarized, the latter measurement would account for possible interstellar polarization, polarization induced by the telescope and instrument, and point-spread function (PSF) variation across the field. At such low significance levels a correction must be applied to the computed values to account for the non-Gaussian nature of the underlying probability distribution (*9*). When corrected for this effect the polarization is found to be 0.0 ± 1.4% using either measurement. This is consistent with no linear polarization and we conclude that an upper limit of 2.3% (95% confidence limit) is set on the linear polarization of the optical afterglow of GRB 990123 on 24.17 January 1999 UT. This upper limit is much stronger than the existing upper limits on the linear polarization of radio afterglows of cosmological GRBs; <19% for GRB 980329 (*10*) and <8% for GRB 980703 (*11*).

The effects of depolarization or interstellar polarization in the Galaxy are expected to be negligible at the high latitude of GRB 990123

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($b = 54.6°$), which is well out of the plane of the Milky Way. For the low Galactic extinction (Fig. 1) the maximum interstellar polarization or depolarization is less than 0.2% (*12*). The light from the optical afterglow passes through the outskirts of a fairly luminous (*13, 14*) dynamically cold (*6, 7*) galaxy. It appears to originate ~1.3 kpc outside a possible starforming region (*15*), and there is no evidence for extinction along its line of sight (*16*). Thus the polarization or depolarization towards GRB 990123 is expected to be negligible. It has been suggested that GRB 990123 may have been gravitationally lensed (*17*). This would not affect the interpretation of our results as lensing leaves the degree of polarization and the direction of the polarization vector unchanged (*18*).

Polarization can be produced by electron scattering in the ejecta left behind by the GRB. The ejecta can be distributed in a spheroidal or aspherical shell (*19*), but clumpy ejecta can also produce some degree of polarization (*20*). The most widely used model of GRB afterglows, however, is that of synchrotron emission from relativistic electrons, originating in a relativistically expanding spherical fireball as it decelerates into an ambient medium (*1*, *21*). The electrons are assumed to be continuously accelerated in the shocked interface between the fireball and the external medium, to a power law distribution in electron energies with index $p > 2$. The resulting spectrum is determined by the synchrotron emission, integrated over the electron distribution, while the light curve is primarily determined by the hydrodynamic evolution of the fireball. In this standard model the required magnetic field is of unknown origin but is assumed to be tangled and in equipartition with the shocked medium.

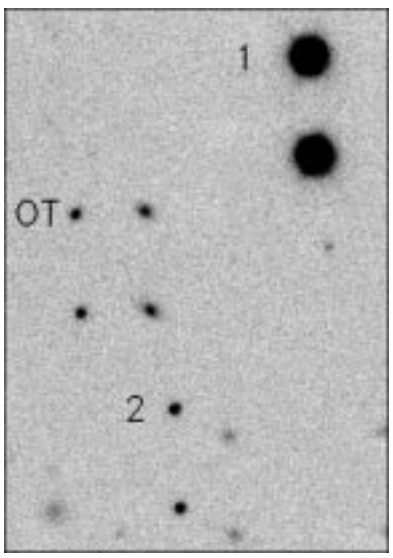

Fig. 1. Excerpt of the combined image containing the 0°/90° orientations. The image measures 60 × 85 arc sec. North is up and east is to the left. The optical transient (afterglow) to GRB 990123 (OT) and two comparison stars (*1, 2*) are indicated for the orientation of 90°. The images corresponding to 0° are shifted 15 arc sec to the south. To correct for pixel-to-pixel sensitivity variations of the CCD, the images were flat fielded with R band twilight sky flat fields. Correction for slowly varying sensitivity variations due to the passage of the light through the calcite blocks was obtained from the dithered images themselves by dividing by a smoothed median image. The photometry was carried out using PSF fitting with the DAOPHOT II/ALLSTAR (*33*) software package. Large fitting radii were employed to minimize the effects of small-scale variations and photon noise. Separate PSFs for the four orientations were used (using the unsaturated bright star 1 as a template).

Although synchrotron radiation in general could be up to 70% polarized (depending on p and the magnetic field configuration), the possibility of a polarized synchrotron radiation has only recently been introduced in the context of GRBs by Gruzinov and Waxman (*22*). They argue that the afterglow radiation is due to a magnetic field behind the shock. The origin of the field is uncertain, but it may be generated in and by the blast wave. As the instantaneous synchrotron spectrum depends only on the conditions at the shock front, a tangled magnetic field would not give rise to polarized emission. However, a coherence length comparable to the thickness of the blast wave could lead to a polarization of up to about 10 $\varepsilon^{3/2}$%, where $\varepsilon < 1$ measures the rate of growth of the coherence length in units of the speed of light (*22*). A coherence length growing at the speed of light would result in ~10% polarization. Polarization at the ~1% level would either imply that the magnetic field generated in the shock would be tangled and confined to the shock front producing no polarized radiation, or that magnetic fields are not effectively generated, implying that the afterglow emission is not of synchrotron origin.

The upper limit on the linear polarization we have obtained translates into $\varepsilon < 0.37$. A possible caveat occurs if the integration time is longer than the time scale in the observer frame on which the polarization varies, in which case all polarization information will be lost. However, according to the estimates of Gruzinov and Waxman (*22*) this time scale is a factor of 10 larger than the 50 minute time span over which the observations reported here were conducted. We thus conclude that the coherence length does not grow sufficiently fast to sustain a large-scale magnetic field structure, at least not on scales comparable to the thickness of the blast wave. The proposed mechanism for generating and sustaining a magnetic field in the fireball is therefore either not generic or the synchrotron emission is not the dominating radiation process. The conclusion that magnetic fields may not have been effectively generated is supported by radio measurements (*16*) indicating that the magnetic field strength of GRB 990123 was very low on 24.65 January UT. The field strength is likely to be time-dependent so that different radiative mechanisms may dominate the flux at different epochs. However, the generation, evolution and lifetime of a magnetic field under blast wave conditions deserve further theoretical study before the dominating radiation mechanisms can be determined. Alternative radiation processes, such as bremsstrahlung and Comptonization, should then be seriously considered.

Table 1. Log of observations. The exposure time was 300 s for all observations. Meteorological conditions were fine and the seeing was ~1.2 arc sec. At the mean epoch of 24.16787 January 1999 UT the mean magnitude of the optical transient was $R = 20.07 \pm 0.02$, assuming a photometric zero point for which $R = 14.52$ for star 1 [Fig. 1 and (*33*)]. After correction for Galactic extinction (*32*) ($A_R = 0.040$ for $E(B\text{-}V) = 0.016$) this corresponds to a flux of $f_\nu = 28.1 \pm 0.5$ μJy.

Time (24 Jan UT)	Orientation (degree)
03:45	0/90
03:51	−45/45
03:56	−45/45
04:02	0/90
04:07	0/90
04:13	−45/45

An alternative to this spherically symmetric model is a scenario in which the afterglow is intrinsically beamed (collimated within a cone of opening angle θ). A beamed source may show considerable linear polarization; in BL Lac objects, which are active galactic nuclei where relativistic jets are aligned along our line of sight, linear polarizations of the order of ~10% are common (*23*). It has been speculated that objects like the Galactic microquasars GRS 1915+105 and GRO J1655–40 (*24*) could produce scaled-down versions of GRBs if their jets are seen at small viewing angles ≤ 10°. In this case, time scales will be shortened by 2Γ (where Γ is the bulk Lorentz factor) and flux densities boosted by $8\Gamma^3$ with respect to the values in the rest frame. In fact, collapsars with $\Gamma > 100$ have been suggested as one of the sources that eventually can lead to a GRB (*25*).

If the afterglow emission is of synchrotron origin and beamed, polarization may be expected if the magnetic field has a component perpendicular to the beam axis. For a random GRB, a viewing angle of the order of θ is favored, since for smaller viewing angles the solid angle decreases, and for larger angles the flux drops. Polarization is maximized for viewing angles near the edge of the beam. The non-detection of polarization may imply that the afterglow was isotropic, as discussed above. Very low polarization, however, also occurs if the viewing angle is close to the beam axis (*26*).

For a fixed viewing angle, a decaying Γ could then give rise to a time varying polarization. The initial G factor has been estimated to be $\Gamma_0 \sim 200$ at the peak of the optical flash (*27*) of GRB 990123. On 24.17 January it would

have decayed to $\Gamma \sim 10$ to 20 (*27*), corresponding to a relativistic beaming angle of ~3° to 6°. The measured upper limit on the polarization is therefore consistent with a small angle between the jet axis and our line of sight. While the probability of observing a jet at such a small viewing angle is small, there is independent evidence for beaming. The steepening of the light curve of the afterglow of GRB 990123, expected when Γ drops below $1/\theta$ (*7*, *28*) was observed about 2 days after the burst (*5*, *7*, *13*, *29*). For $\Gamma \approx 5$ this corresponds to a jet opening angle of $\theta \sim 10°$. If the same beaming angle applies to the γ-rays (*30*) then the emitted energy in γ-rays alone is $E_\gamma \approx 8 \times 10^{52}$ erg (assuming a two-sided jet emission). The constraints on GRB formation scenarios are then considerably relaxed and possibly within reach of popular models based on stellar deaths.

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Spectroscopic Limits on the Distance and Energy Release of GRB 990123

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An optical spectrum of the afterglow from the unusually bright gamma-ray burst GRB 990123 obtained on 24.25 January 1999 universal time showed an absorption system at a redshift of $z = 1.600$. The absence of a hydrogen Lyman α forest sets an upper limit of $z < 2.17$, while ultraviolet photometry indicates an upper limit of $z < 2.05$. The probability of intersecting an absorption system as strong as the one observed along a random line of sight out to this z is at most a few percent, implying that GRB 990123 was probably at $z = 1.600$. Currently favored cosmological parameters imply an isotropic energy release equivalent to the rest mass of 1.8 neutron stars (4.5×10^{54} erg) was emitted in gamma-rays. Nonisotropic emission, such as intrinsic beaming, may resolve this energy problem.

Intense bursts of gamma-rays, lasting from a fraction of a second to a couple of minutes, have been observed for three decades (*1*). During the past 2 years, ground-based follow-up observations have shown that almost all gamma-ray bursts (GRBs) with an optical afterglow have a cosmological origin (*2*). On 23 January at 9:47:14 universal time (UT), GRB 990123 was detected by the Italian-Dutch x-ray satellite BeppoSAX, several instruments on board the Compton Gamma Ray Observatory and other spacecraft. For BeppoSAX, this was the brightest GRB to date (*3*). The optical afterglow was identified shortly thereafter (*4, 5*). Optical emission with a magnitude of V = 8.95 at its maximum brightness was observed about 47 s after the start of the burst (GRB 990123 lasted about 100 s). The near coeval observations of a GRB and optical emission indicates that GRBs are associated with optical transients.

We obtained spectroscopic observations with the 2.56-m Nordic Optical Telescope (NOT), situated at Roque de Los Muchachos in La Palma, Canary Islands, on 24 January 1999 UT. The Andalucía faint object spectrograph and camera (ALFOSC) was used in long-slit mode with a 2048 × 2048 pixel charge-coupled device (CCD) detector, binned to a 1024 × 1024 pixel format to minimize detector noise. ALFOSC was configured with a 1.″2 wide slit and a 600 lines mm^{-1} grism blazed at 5600 Å. This gave a wavelength coverage from 3820 to 6830 Å with a dispersion of 3.0 Å per binned pixel

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