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Evolution of the polarization of the optical afterglow of the γ-ray burst GRB030329

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The association of a supernova with GRB030329[1,2] strongly supports the 'collapsar' model[3] of γ-ray bursts, where a relativistic jet[4] forms after the progenitor star collapses. Such jets cannot be spatially resolved because γ-ray bursts lie at cosmological distances; their existence is instead inferred from 'breaks' in the light curves of the afterglows, and from the theoretical desire to reduce the estimated total energy of the burst by proposing that most of it comes out in narrow beams. Temporal evolution of the polarization of the afterglows[5–7] may provide independent evidence for the jet structure of the relativistic outflow. Small-level polarization (∼1–3 per cent)[8–17] has been reported for a few bursts, but its temporal evolution has yet to be established. Here we report polarimetric observations of the afterglow of GRB030329. We establish the polarization light curve, detect sustained polarization at the per cent level, and find significant variability. The data imply that the afterglow magnetic field has a small coherence length and is mostly random, probably generated by turbulence, in contrast with the picture arising from the high polarization detected in the prompt γ-rays from GRB021206 (ref. 18).

GRB030329 triggered the High Energy Transient Explorer, HETE-II, on 29 March 2003 (11:37:14.67 UT)[19]. The discovery of the burst optical afterglow[20,21] was quickly followed by a redshift measurement[22] for the γ-ray burster of $z = 0.1685$ (∼800 Mpc), thus making GRB030329 the second-closest long-duration[23] γ-ray burst ever studied, after GRB980425 (ref. 3). The proximity of GRB030329 resulted in very bright prompt and afterglow emission, leading to the best-sampled afterglow to date. Detailed optical spectroscopy revealed an underlying supernova (SN2003dh)[1,2] with an astonishing spectral similarity to SN1998bw (at

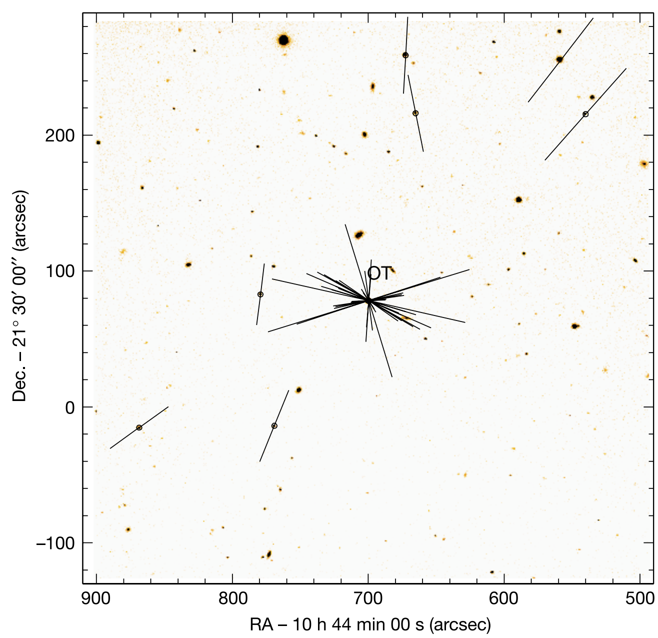

Figure 1 R band image of the field centred on the optical afterglow of GRB030329. The 27 FORS1 (Focal Reducer and Low Dispersion Spectrograph at the Very Large Telescope (VLT)/Antu) measurements are shown as 'vectors' where the length is a measure of the polarization degree, and the orientation indicates the position angle. While the afterglow varies in degree as well as angle, the polarization of seven field stars is constant within 0.1% in polarization degree and 1.5 degree in position angle throughout the 38 days. Linear polarization was measured from sets of exposures with different retarder-plate position angles. Imaging polarimetry was obtained during the first four nights (when the afterglow was brighter than 17th magnitude) from sixteen different retarder-plate angles, and from eight angles thereafter. Because the FORS1 polarization optics allows determination of the degree of polarization to an accuracy of $<3 \times 10^{-4}$ and of the polarization angle to ∼0.2°, we consider the above variance of the field stars to represent the systematic error over the 38-day time period. Observations of polarimetric standard stars reproduced their tabulated values within 5%. The FORS1 retarder-plate zero-point angle of −1.2° was subtracted from the polarization angle. The position angle has a systematic uncertainty of ±1.5°, which was added in quadrature to the statistical errors. OT, optical transient.

$z = 0.0085$, associated with GRB980425 (ref. 3)), thus strongly supporting the link of long-duration γ-ray bursts with core-collapse supernovae.

The apparent brightness of GRB030329 also afforded a unique opportunity to study the temporal evolution of polarization in the afterglow phase. Previous single measurements found low-level (1–3%) polarization[8–15] in optical afterglows, and the only reports on variable polarization[16,17] were based on few measurements with different instruments and modest signal-to-noise ratios. We have overcome the previous sampling limitations with 31 polarimetric observations of the afterglow of GRB030329 obtained with the same instrumentation (plus a few more with different instruments) over a time period of 38 days for a total of an unprecedented ~50 h of observations with an 8-m telescope. Here, for the first time, we establish a polarization light curve for an optical γ-ray burst afterglow.

We performed relative photometry, and from each pair of simultaneous measurements at orthogonal angles we derived the Stokes parameters U and Q. To obtain the intrinsic polarization of the γ-ray burst afterglow, we have to correct for Galactic interstellar polarization due to dust. We performed imaging polarimetry to derive the polarization parameters of seven stars in the field of GRB030329, and obtained an interstellar (dust) polarization correction of 0.45% at position angle 155°. Subtraction of the mean foreground polarization was performed in the Q–U plane ($Q_{\rm fp} = 0.0027 \pm 0.0013$, $U_{\rm fp} = -0.0033 \pm 0.0017$). Figure 1 shows an R-band image of the GRB030329 field with the polarization 'vectors' superimposed.

The temporal evolution of the degree and angle of polarization together with the R-band photometry is shown in Fig. 2. This figure demonstrates the presence of non-zero polarization, $\Pi \approx 0.3$–2.5% throughout a 38-day period, with significant variability in degree and angle on timescales down to hours. Further, the spectropolarimetric data of the first three nights as well as the simultaneous R- and K-band imaging polarimetry during the second night show that the relative polarization and the position angle are wavelength-independent (within the measurement errors of about 0.1%) over the entire spectral range. These data imply that polarization due to dust in the host galaxy of GRB030329 does not exceed ~0.3%. Dust destruction in the vicinity of the γ-ray burst due to the strong radiation field would probably result in a monotonically decreasing polarization degree, which is not observed during the first days. We therefore conclude that the bulk of the observed variability is intrinsic to the afterglow.

Figure 2 shows that while the polarization properties show substantial variability (for which no simple empirical relationship is apparent), the R-band flux is a sequence of power laws. During each of the power-law decay phases the polarization is of the order of a few per cent, different from phase to phase, and variable within the phase, but not in tandem with the 'bumps'and 'wiggles' in the light curve. We observe a decreasing polarization degree shortly after the light curve break at ~0.4 days (as determined from optical[21,24] and X-ray data[25,26]). Rapid variations of polarization occur ~1.5 days after the burst, and could be related to the end of the transition period towards a new power-law phase starting at ~1.7 days. Polarization eventually rises to a level of ~2%, which remains roughly constant for another two weeks. Late in the observation campaign the underlying type Ic SN2003dh[1,2] increasingly contributes to the total light and probably also to the observed polarization properties. Asymmetries in this type of supernova can produce polarization of the order of 1% (refs 27, 28), as we observe towards the end of our campaign.

GRB030329 belongs to a growing group of bursts for which densely monitored afterglow light curves show significant 'bumps' and 'wiggles' relative to a simple power-law decay (most notably GRB021004 and GRB011211). These bumps and wiggles complicate the interpretation of the polarization properties. While the rapid decrease in polarization degree during the first night is consistent

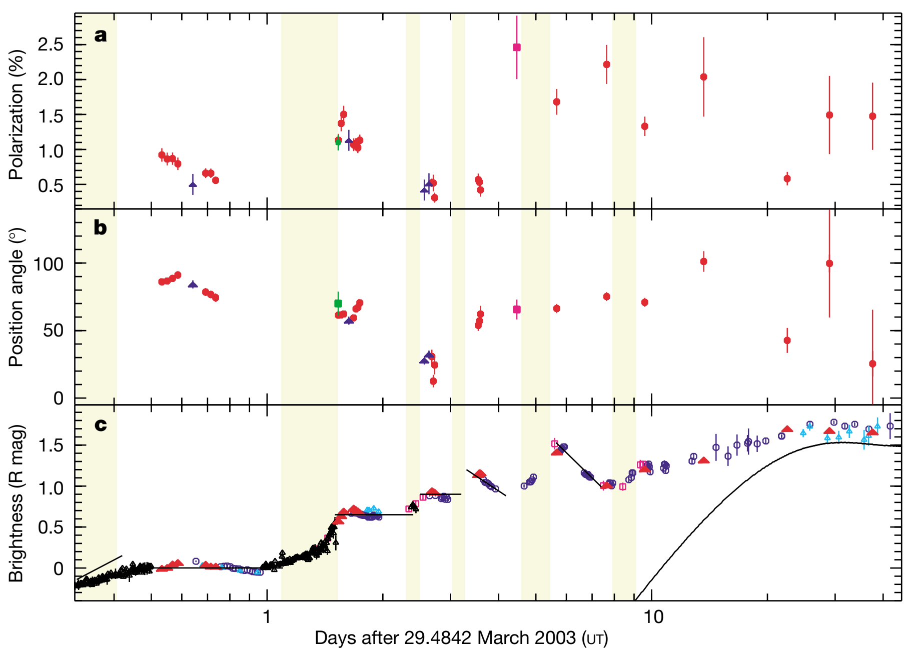

Figure 2 Evolution of the linear polarization during the first 38 days. **a**, **b**, The polarization degree in per cent and the position angle in degrees. The red data points are from imaging polarimetry with FORS1/VLT. Spectropolarimetry (blue symbols, 700–800 nm range) was performed during the first three nights. The green points were obtained with CAFOS at the 2.2-m telescope at Calar Alto on 30/31 March. The magenta data point was obtained with AFOSC at the 2.56-m NOT telescope on 2 April 2003. **c**, The residual R-band light curve after subtraction of the contribution of a power law $t^{-1.64}$ describing the undisturbed decay during the time interval 0.5–1.2 days after the γ-ray burst (that is, after the early break at 0.4 days), thus leading to a horizontal curve. The symbols correspond to data obtained from the literature (black), the 1-m USNO telescope at Flagstaff (blue), the OAN Mexico (light blue), and FORS1/VLT (red). Lines indicate phases of power-law decay, with the first one from early data[21] (not shown). Yellow bars mark re-brightening transitions. Contributions from an underlying supernova (solid curved line) do not become significant until ~10 days after the γ-ray burst.

with the model predictions[5–7], the position-angle changes are not, and thus it remains to be proven whether or not these early polarization data support the break at 0.4 days as being due to a jet. A connection to theoretical models throughout the entire period covered in Fig. 2 is a daunting task. A detailed comparison of our data with characteristic features of various theoretical models is beyond the scope of this paper, and will be presented elsewhere.

Thus our data, to our knowledge, constitute the most complete and dense sampling of the polarization behaviour of a γ-ray burst afterglow to date. For GRB030329 we conclude that the afterglow polarization probably did not rise above $\sim$2.5% at any time, and that the polarization did not correlate with the flux. The low level of polarization implies that the components of the magnetic field parallel and perpendicular to the shock do not differ by more than $\sim$10%, and suggests an entangled magnetic field, probably amplified by turbulence behind shocks, rather than a pre-existing field. This is in contrast with the high level of polarization detected in the prompt γ-rays from GRB021206[18] and suggests a different structure and origin of the magnetic field in the prompt versus afterglow emission regions. Evolving polarization properties provide a unique diagnostic tool for γ-ray burst studies, and the extremely complex light curve of the optical afterglow of GRB030329 emphasizes that measurements should be carried out with high sampling frequency. □

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Experimental observation of symmetry-breaking nonlinear modes in an active ring

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Solitons are large-amplitude, spatially confined wave packets in nonlinear media. They occur in a wide range of physical systems, such as water surfaces, optical fibres, plasmas, Bose–Einstein condensates and magnetically ordered media[1,2]. A distinguishing feature of soliton behaviour that is common to all systems, is that they propagate without a change in shape owing to the stabilizing effect of the particular nonlinearity involved[1,3]. When the propagation path is closed, modes consisting of one or several solitons may rotate around the ring, the topology of which imposes additional constraints on their allowed frequencies and phases[4,5]. Here we measure the mode spectrum of spin-wave solitons in a nonlinear active ring constructed from a magnetic ferrite film. Several unusual symmetry-breaking soliton-like modes are found, such as 'Möbius' solitons, which break the fundamental symmetry of 2π-periodicity in the phase change acquired per loop: a Möbius soliton needs to travel twice around the ring to meet the initial phase condition.

Despite the numerous publications on nonlinear wave propagation[1–3,6,7], multi-soliton modes in confined nonlinear systems have received very little attention to date. Very recently Carr *et al.* analysed multi-soliton modes in a box with infinitely high walls and, equivalently, a ring[4,5], and they find that the symmetry of these modes can differ from that of linear modes of the system. The linear modes of a box are sinusoidal standing waves enumerated by the number of half-wavelengths that satisfy the box size. There is a direct connection between the mode number of a linear mode and its mirror symmetry with respect to the centre of the box: odd and even modes are symmetric and antisymmetric, respectively. It was shown[5] for the case of an 'attractive nonlinearity' necessary for solitons to form that nonlinear modes can be classified by the number of solitons comprising a particular mode. However, there is no general connection between the symmetry properties of a mode and the number of the solitons. For example, two modes consisting of two solitons are reported: one mode is antisymmetric and the other is symmetric with respect to the box centre. The symmetry of the former mode corresponds to the symmetry of the linear mode with two half-wavelengths, while the latter mode has no linear counterpart and was therefore termed a 'symmetry-breaking mode'.

As a model system, we constructed an active nonlinear ring based

