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# Probing GRB afterglows with deep linear and circular polarimetry: GRB 091018

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Follow-up observations of large numbers of gamma-ray burst (GRB) afterglows, facilitated by the Swift satellite, have produced a large sample of spectral energy distributions and lightcurves, from which the basic micro- and macrophysical parameters of afterglows may be derived. However, a number of phenomena have been observed that defy explanation by simple versions of the standard fireball model, leading to a variety of new models. Polarimetry can be a powerful diagnosis of afterglow physics, probing the magnetic field properties of the afterglow and geometrical effects (e.g. jet breaks). Unfortunately, high quality afterglow polarimetric curves are difficult to acquire.

In this paper we present the first multi-night, high quality, multicolour, polarimetric lightcurve of a Swift GRB afterglow, using the Very Large Telescope. We obtained a linear polarimetric curve of GRB 091018 in $R$ band, from 0.13 to 2.3 days after burst. We probe the ordered magnetic field component through deep circular polarimetry in $R$ band, finding $P_{\rm circ} < 0.15\%$, the deepest limit yet for a GRB afterglow. We probe host galaxy dust induced polarisation using deep $Ks$ band polarimetry, combined with optical and near-infrared spectroscopy. We add high quality optical and near-infrared broadband lightcurves and spectral energy distributions (hours to weeks after burst), and thereby form one of the most complete datasets to date of a "normal" GRB. Using this dataset we derive an overall view of the properties of the jet and the engine from which it emerged; and probe the magnetic field and particle acceleration physics in the blast wave. Finally, we demonstrate first observations of a campaign to probe GRB afterglow polarisation in near-infrared bands using the William Herschel Telescope, in an effort to sample polarisation redwards of the wavelength $\lambda_{\rm max}$, the wavelength of maximum dust scattering induced polarisation.

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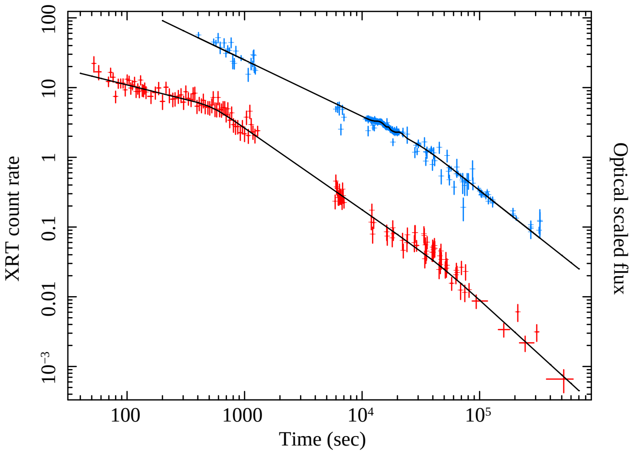


**Figure 1:** Red: Swift XRT X-ray light curve of the afterglow of GRB 091018; blue: optical and near-infrared light curve. Both light curves require a break at the same time, $3.23 \times 10^4$ s, likely the jet break.

## 1. Introduction

Linear and circular polarimetry form powerful probes of the physics of GRB afterglows, allowing us to determine parameters (e.g the jet structure, magnetic field configuration, etc) that can not easily be measured from lightcurves alone (e.g. [1]). The observed richness in afterglow light curve morphology, in particular in X-rays, has resulted in several new models with various additional components to the standard fireball model, including for example the effects of high latitude emission, variable microphysics, energy injection mechanisms, etc. Direct tests of these models require high quality spectral energy distributions (SEDs) for a large number of sources, often not available. Polarimetry can provide independent evidence. Unfortunately, GRB afterglows show only low values of linear polarisation, and fade very rapidly, requiring a large effort (and some luck!) to obtain well sampled, high accuracy polarisation curves. In this paper we describe some selected results from our large polarimetry campaign of GRB 091018: the first multi-night, high accuracy polarimetric study of a Swift GRB [2].

## 2. Afterglow light curves and spectral energy distributions

After the detection of GRB 091018 by Swift, we observed its afterglow using several telescopes and instruments. Data from all filters were combined through a free offset fit (i.e. we assume data from all filters have the same temporal decay but relative offsets are fit). The resulting light curve is shown in Figure 1. Both X-ray and optical data require a break, at $3.2 \times 10^4$ seconds. Fits on afterglow SEDs at 10, 30 and 100 kiloseconds show no sign of spectral evolution: the break is consistent with being achromatic. We interpret this break as a likely jet break, though the post break slopes are somewhat shallower than expected (see [2] for details).

## 3. Linear polarisation curve

We acquired 20 sets of linear polarimetry data in *R* band using the FORS2 instrument on VLT: the largest polarimetry dataset for a GRB since GRB 030329. The first set started at 0.13 days after

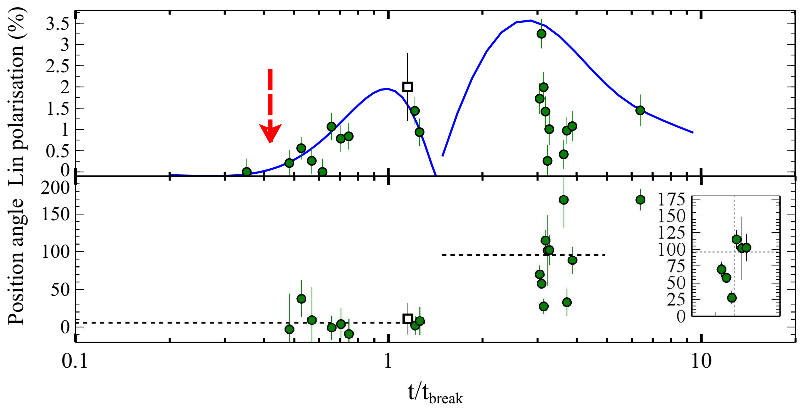


**Figure 2:** All linear polarisation data, corrected for polarisation induced by Galactic dust, plotted as a function of the time since burst divided by the time of the break in the optical light curve (i.e. $t_{\rm break} = 3.23 \times 10^4$ seconds). The red arrow points at the time at which the circular polarisation was acquired. Overplotted in blue is the model [1] for a homogeneous jet with a jet break at $t_{\rm break}$ that does not experience sideways expansion, with viewing angle $\theta_{\rm obs} = 0.2\theta_{\rm jet}$. The model has been shifted slightly (by dividing the model $t/t_{\rm jet}$ by 1.15). The lower panel shows the polarisation position angle. The dotted line for $t/t_{\rm jet} < 1.5$ shows the average position angle (6 degrees). The dotted line for $t/t_{\rm jet} > 1.5$ is set at 96 degrees: the average value before this time plus 90 degrees, to show the predicted 90 degree position angle swing. The inset shows the rapid polarisation rotation at $t/t_{\rm break} \sim 3.16$ (vertical dotted line in inset), with the horizontal dotted line at a position angle of 96 degrees.

burst, the last at 2.4 days. Exposure times were chosen to provide statistical polarisation errors smaller than 0.3% throughout. We refer to [2] for details on calibration and observing strategy. We use field stars which have errors smaller than 0.3% to measure the polarisation induced by scattering of Galactic dust, selecting the stars within $2'$ from the instrument optical axis to reduce the effects of the (largely radial) instrumental polarisation. We fit the resulting $(Q/I, U/I)$ distribution of field stars with a 2 dimensional Gaussian distribution, and use the fitted centre as the Galactic dust induced polarisation offset. The width of the fitted Gaussians is propagated into the errors of the GRB polarisation points. The resulting, Galactic polarisation corrected, linear polarisation curve is shown in Figure 2, plotted in units of time since the burst, $t$, normalised by the jet break time $t_{\rm break}$. Overplotted in that Figure is an analytical model from [1] that describes the expected behaviour of a homogeneous, non-sideways spreading jet seen at a small angle. Jet break models predict two bumps in the polarisation curve, with a 90 degree angle difference between the two bumps. This has not been observed before, because *(i)* bursts with long timescale polarisation monitoring have been showing large bumps in their light curve [3] or *(ii)* the jet break was not covered by the observations. Our data of GRB 091018 are arguably the first case where a jet break is covered by polarimetry, and indeed the data shows a two-bump structure, with a 90 degree angle change between the first and second bump. However, the second polarisation bump shows unpredicted complexity: a short time-scale variability in $P$ and $\theta$ is seen. This can be well reproduced by the presence of an additional polarisation component with a angle $\theta$ nearly orthogonal to the jet break associated polarisation component.

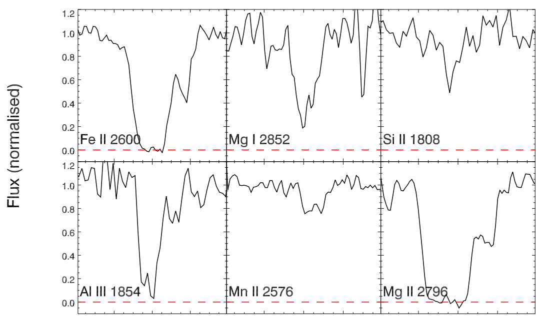


**Figure 3:** A small selection of absorption lines detected in the X-shooter spectrum of the afterglow of GRB 091018. The stronger, saturated, lines show clear evidence for at least three discrete velocity components, with different abundances.

## 4. Multicolour polarimetry and dust scattering

To verify that the polarisation we measure is due to the afterglow, we obtain *Ks* band polarimetry using the ISAAC instrument on the VLT, quasi-simultaneous with an *R* band measurement. The afterglow polarisation is likely wavelength independent over this range, whereas polarisation caused by dust scattering in the host galaxy should be strongly wavelength dependent, in a way that depends on the dust grain size distribution. Comparing our *R* and *Ks* polarimetry we see no clear signs of polarisation from dust in the host. The *Ks* datapoint is shown as a square in Figure 2. We obtained high-quality spectroscopy of the afterglow using X-shooter on the VLT (Figure 3) - the gas phase metal abundances can be combined with SEDs and polarimetry to get further insight into the dust properties in this sightline.

## 5. Circular polarimetry

As part of our polarimetric campaign we also acquired deep *R* band circular polarimetry using VLT FORS2. The circular polarisation exposures were obtained directly after the first linear polarisation set, to make use of the brightness of the afterglow at the time. We detect no circular polarisation, with a $2\sigma$ limit $P_{\rm circa} < 0.15\%$. This is the deepest limit to date, and strongly climates the existence and the effects of any ordered magnetic field.

## 6. Future work

### 6.1 Early to late

Recently, dedicated instruments on robotic telescopes have been successful in acquiring polarimetry of afterglows very rapidly after the burst, probing reverse shocks and other phenomena that dominate early-time behaviour (e.g. [4]). In addition, the first prompt emission $\gamma$-ray polarisation values have been determined by a dedicated instrument [5]. A late time polarimetry

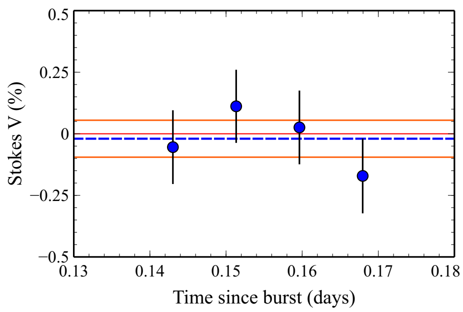


**Figure 4:** Shown are the four datasets making up the deep circular polarimetry, with on the vertical axis $100 \times V/I$. The dashed blue line and the orange lines show the combined value $V/I = -0.0002 \pm 0.00075$, leading to a $2\sigma$ limit of $P_{\rm circ} < 0.15\%$.

campaign such as the one presented here for GRB 091018, for a burst with prompt and/or early afterglow polarimetry would be particularly interesting, to track the transition from prompt emission to "classical" afterglow.

### 6.2 Redwards of $\lambda_{\rm max}$

To date, no convincing evidence for dust scattering induced polarisation has been found in GRB afterglows. However, GRBs form in star forming regions in which dust formation and destruction is taking place. Studies of SEDs of large samples of GRBs have shown that most afterglows experience only mild host galaxy reddening $A_V$, but a significant fraction of GRBs show dust columns that should be detectable through wavelength dependent polarisation, see Figure 5. Detection of dust scattering induced polarisation can, in combination with optical SEDs and spectroscopy, lead to a greater understanding of the dust properties in GRB sight lines, including the destruction of dust by the GRB itself. To get more insight into this issue, we aim to acquire a sample of linear polarimetric measurements in the *Ks* band: at redshifts $z < 3$ this is red ward of the wavelength $\lambda_{\rm max}$ at which the dust polarisation is at maximum, see Figure 5. We use the LIRIS instrument on the 4.2m William Herschel Telescope for this purpose. LIRIS utilises a double Wollaston configuration to obtain simultaneous measurements of the polarised flux at angles 0, 90, 45 and 135 degrees, with a $1' \times 4'$ field of view. By rotating the instrument we can improve calibration (a 90 degree rotation results in a half rotation in Stokes parameter space) and increase the number of available field stars to use as secondary calibrators. Using this approach, we have so far successfully observed two GRBs, one of which now identified as a tidal disruption event, GRB 110328 (Swift J164449.3+573451). The latter source showed a significant detection of 7.4% polarisation in our *Ks* data [6] (Figure 6), which, in combination with deep polarisation limits at radio wavelengths [6], provides evidence for the presence of a relativistic jet. These data demonstrate the feasibility of performing polarimetry with 4m class telescopes also in the infrared.

## References

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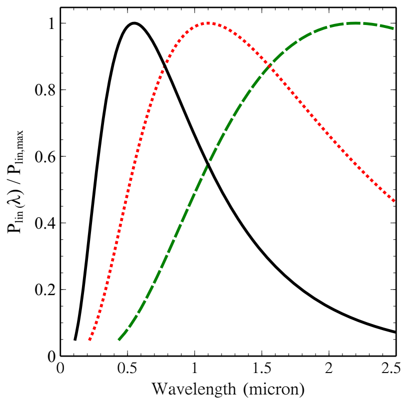


**Figure 5:** The Serkowski curve, which gives an empirical description of the polarisation as a function of wavelength in the case of dust scattering, drawn at $z = 0$ in black. The curve is characterised by a typical wavelength $\lambda_{max}$ at which maximum polarisation $P_{max}$ is present. The red and green (dotted and dashed) curves show the same curve at $z = 1$ and $z = 3$, respectively.

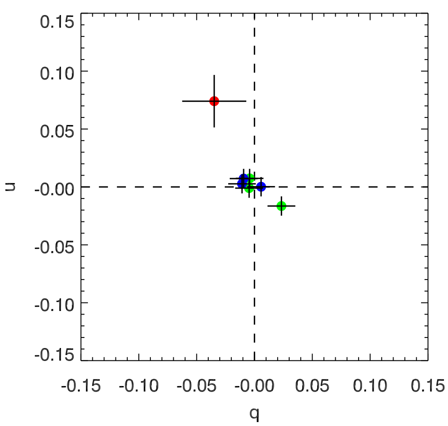


**Figure 6:** *Ks* band polarisation measurement using LIRIS on the WHT: this plot shows Stokes parameters $q = Q/I$ and $u = U/I$ of objects in our data of GRB 110328, where bright field stars are shown in green and blue (their centre shifted to $(q,u) = (0,0)$), and the GRB in red, clearly offset from the field stars.


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