Polarization curves of GRB afterglows predicted by the universal jet structure

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1 Introduction

Detections of linear polarization in the optical afterglow of GRBs are accumulating fast since the first measurements in GRB 990510 [1], [15]. It was soon proposed that the observed polarization could arise from observing a collimated fireball with a slightly off-axis line of sight ([3], [14]). As a consequence, it was also realized that the degree of polarization could be connected with the achromatic break in the lightcurve expected in jetted fireballs. The polarization starts to grow when the observer perceives the nearest edge of the jet and the lightcurve begins to steepen; it has two maxima with the position angle being orthogonal to each other and then it slowly fades away while the jet front becomes entirely visible and the flux accomplishes the transition between the two asymptotic power–laws (Fig. 4 in [3]). Recently a different structure for the emission pattern has been proposed: a jet with a brighter (maybe faster) spine surrounded by dimmer (and slower) wings, with a standard energy reservoir [9], [11], [13], [16]. The main parameters of such a structured jet are the angular size of the core $\theta_{\text{core}}$ and the wings luminosity distribution. We [11] have shown that if the luminosity goes as $\theta^{-2}$ for $\theta > \theta_{\text{core}}$, the lightcurves from such a jet are virtually indistinguishable from an homogeneous one (see [1]) and both models can reproduce the break time–luminosity correlation [2], [8]. Actually while in the standard model the time at which there is a steepening in the power–law decay of the afterglow, is related to the cone angle of the jet, in the structured jet such a break in the afterglow lightcurve occurs at a time that depends on the viewing angle. Instead of implying a range of intrinsically different jets – some very narrow, and others with similar power spread over a wider cone – the data on afterglow breaks are consistent with a standardized jet, viewed from different angles. Since each luminosity is univocally related to a viewing angle, it is possible to calculate the predicted luminosity function [11]; in the simplest version of this model, $n(L) \propto L^{-2}$. This prediction, if robustly confirmed by observations, could support the universal jet structure, but it cannot rule out the standard model.
For this reason and the similarity of the lightcurves it is important to look for observations that can discriminate between the two different structures and we show in the following that polarization can be such a powerful tool.

Figure 1: Lightcurves for a structured jet (black line) seen at $6^\circ$ with $E_{iso}(6^\circ) = 10^{53} \text{erg}$ and an homogeneous jet (red line) seen on axis with an opening angle of $\theta_{jet} = 12^\circ$ and isotropic equivalent energy $E_{iso} = 10^{53} \text{ erg}$. The 2 lightcurves have the same break time and asymptotic slopes; they differ only up to a factor of 1.5 around the break time.

2 The model

We assume that the jets emerging from the central engine of GRBs are characterized by the following distributions in energy and initial Lorentz factor:

$$E_{iso} = \frac{E_c}{[1 + (\theta/\theta_c)^2]}$$ (1)

$$\Gamma_o = \frac{\Gamma_c}{[1 + (\theta/\theta_c)^\alpha]}.$$ (2)

For simplicity we assume azimuthal symmetry. We take $\frac{\Delta \log(\Gamma_o)}{\Delta \theta} \leq 1$, therefore the regions with different $\Gamma_o$ and energy are causally disconnected and they evolve independently. We can therefore treat separately the evolution of each point of the jet, assuming adiabatic expansion. Our code integrates numerically the equation of relativistic energy conservation and calculates consistently the evolution of the jet aperture, if sideway expansion is considered (for the homogeneous jet see e.g. [10], [5]). If
and how post shock pressure gradients develop in the case of a structured jet is a many parameters problem, that can be solved only through hydrodynamic simulations. We therefore use a parametric analytic treatment of the sideways expansion, where we can choose how the lateral velocity change with \( \theta \) and its maximum value. We calculate the comoving frame intensity assuming the standard synchrotron equations (\( [7] [4] \)). To compute the polarization vector we assume a magnetic field configuration which corresponds to the compression in one direction of an initially tangled magnetic field: it has some degree of alignment seen edge on while it is still completely tangled on small scales in the uncompressed plane. The maximum value of polarization \( P_0 \) is carried by the light coming from an angle of \( 1/\Gamma \) with the line of sight. We take \( P_0 = 60\% \), that corresponds to a completely ordered magnetic field in the sky plane. In order to compute lightcurves and polarization curves, local luminosities and polarization vectors are then summed over equal arrival time (\( T \)) surfaces,

\[
T = t_{\text{lab}} - \frac{r}{c} \cos(\tilde{\theta}),
\]

where \( r \) is the radial distance from the source, \( \tilde{\theta} \) is the angular distance from the line of sight and

\[
t_{\text{lab}} = \int \frac{dr}{\beta c},
\]

is the time in the laboratory frame.

In this proceeding we show only the results for a non lateral expanding jet, evolving in a constant density medium. A more complete treatment (with sideways expansion) will be completed soon [12].

### 3 Results

The results are summarized in Fig. 3 where we show the lightcurves for the total and the polarized fluxes for different viewing angles. The crucial parameters is the ratio between the viewing angle and the size of the core:

\[
\frac{\theta}{\theta_c} \simeq (t_b/t_{bc})^{1/2},
\]

where \( t_{bc} \) is the achromatic break time expected in the afterglow lightcurve for on–axis observers.

Fig. 3 shows that the more detailed calculations we have now performed confirm all the main features described in our previous paper [11] and allow a more precise description of them. For \( \theta/\theta_{core} \geq 4 \) the lightcurves exhibit a mild flattening around the break time, increasing with the off axis angle, while for \( \theta/\theta_{core} < 4 \) the flattening is not evident and the curves show sharp breaks and they look very similar. This flattening is due to the light coming from the core of the jet. This contribution
Figure 2: Polarization curves for a structured jet (black line) and an homogeneous jet (red line) seen at $\theta = 0.67\theta_{jet}$ (the average off-axis angle). The parameters are the same as Fig.1. The maximum value is $P_0 = 60\%$, that corresponds to a completely ordered magnetic field in the sky plane. These curves can therefore be considered as upper limits. For $P > 0$ the polarization vector lies on the plane containing the line of sight and the jet axis; for $P < 0$ it is rotated by 90°. The most noticeable differences between the structured and the homogeneous jet are that in the former case there is not change in the polarization angle and the maximum is reached around the break time.

reaches its maximum when $1/\Gamma_c \simeq \theta_o$, shortly after $1/\Gamma(\theta_o) \simeq \theta_o$ (see also Eq.8 in \cite{11}); moreover its peak flux is comparable to the line of sight contribution at that time. Therefore this excess modifies the total lightcurve around the time break, and the result is a flattening.

For a fixed viewing angle the direction of the vector is constant, and the magnitude is characterized by one maximum around the break time, when the central and most luminous part of the jet becomes visible. While the rising and fading slopes of the curve are independent of the off–axis angle, the value of the maximum increases with the viewing angle (see lower panel of Fig. 3). This behavior is very different from the one predicted in the homogenous jet model, (see Fig. 2), despite the similarity in the lightcurves (see Fig. 3). For this reason we suggest that a monitoring of the change in the degree of polarization within one burst, especially before and after the break, can help to discriminate between the two models.
Figure 3: Structured jet with parameters: \( E_{\text{core}} = 10^{54} \text{ erg}, \theta_{\text{out}} = 30^\circ, \theta_c = 3^\circ, \Gamma_c = 10^4, \alpha_T = 2, \epsilon_e = 0.1, \epsilon_B = 0.01, n = 1 \text{ cm}^{-3} \). See text for discussion.

References

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Discussion

**J. Rhoads:** You have taken an angular dependence of $\theta^{-2}$ and a standard jet energy in your model. Are these taken for theoretical elegance, or are they demanded by the data? I.e., if we suppose exponents from 1.8 to 2.2 and a factor of 3 or 10 spread in energy, is that consistent with the data?

**E. Rossi:** To be consistent with data the exponent can range between 1.5 and 2.2 (1 $\sigma$ error). (See Fig. 4 in [11]). The value of 2 corresponds to no spread in the observed $\gamma$-ray energy.

**C. Fendt:** From astrophysical jet simulations are known quite well the profiles of the dynamical parameters across the jet. These may, however, completely be disturbed in the shock. Therefore, from observations of the inhomogeneous shell we can hardly derive any clue on the jet formation in the central engine. Could you please comment on that?

**E. Rossi:** The inhomogeneous model we propose holds from a radius of $\sim 10^{13}$ cm and as all the other models for the fireball evolution, the jet’s structure does not retain the imprint of the central object. From such a radius ahead, nevertheless, the inhomogenities in the jet are not destroyed by the shock because any patches is causally disconnected.