The Polarization Variability in the Optical Afterglow of GRB 990712
\textbf{ABSTRACT}

In a recent paper, Rol and colleagues present evidence for a variable polarization in the optical afterglow following the gamma-ray burst GRB 990712. The variation is highly significant, but the position angle appears time independent. Contrary to their conclusion, we point out that this can in fact be explained with existing afterglow models, namely that of a laterally expanding jet.

\textit{Subject headings:} gamma rays: bursts — radiation mechanisms: synchrotron — polarization

1. Introduction

It is generally accepted that the optical emission from gamma-ray burst afterglows is synchrotron radiation from relativistic electrons (e.g. Mészáros & Rees 1997). Models of optical afterglows based on synchrotron emission, and either spherical or collimated outflow geometry have successfully been applied to a number of sources (e.g. Galama et al. 1998; Bloom et al. 1998; Holland et al. 2000). As synchrotron radiation under favorable conditions can be up to 70\% polarized, polarization measurements of optical afterglows have recently been added to the tool box of afterglow researchers.

The first attempt, by Hjorth et al. (1999), resulted in an upper limit of 2.3\% for the polarization of GRB 990123 about 18.3 h after the burst. The polarization level of GRB 990510 was successfully measured by Covino et al. (1999) about 18.5 h after the burst, and Wijers et al. (1999) about 2 h later. These latter measurements were obtained using the same instruments on the same telescope and the polarization remained constant at 1.7\% during the 2 hour interval. Wijers et al. (1999) obtained an additional measurement
at burst age of 43.3 h, but the polarization level at that time was marginally detectable at similar level, mainly due to the faintness of the source and worse observing conditions.

In a recent preprint, Rol et al. (2000), present polarization measurements of GRB 990712 at three different burst ages, 10.6, 16.7 and 34.7 h after the gamma ray event. The polarization level varied between the three measurements from 2.9% ± 0.4% to 1.2% ± 0.4% and 2.2% ± 0.7%, respectively. An interesting part of the result is that the position angle does not seem to vary over the 24 h period from the first to the last data point. Rol et al. (2000) conclude, based on the constant position angle they find, that none of the existing models can successfully explain their result. The purpose of this Letter is to point out that it is in fact possible to obtain varying degree of polarization and a constant position angle in beamed models.

2. Variable Polarization From a Collimated Outflow

Several models have been put forward to explain how a polarized emission may arise in an optical afterglow, despite the fact that the magnetic field generated is expected to be highly tangled with no preferred direction and therefore no net polarization. Examples include the spherically symmetric model of Gruzinov & Waxman (1999), and the polarization scintillation model of Medvedev & Loeb (1999). Recently, Sari (1999; hereafter referred to as S99) and Ghisellini & Lazzati (1999; hereafter GL99), independently and simultaneously, showed that a non-zero and variable polarization can arise from an almost totally tangled magnetic field that has some degree of alignment, if the emission arises in a collimated outflow, and the observers line of sight is located off the outflow axis but within the collimated beam. This polarization variability is essentially a geometrical effect, the most important points being the following (we will assume here that all geometries are conical and we refer the reader to Fig. 2 in GL99 and Figs. 2 and 3 in S99): Initially,
when the expansion is highly relativistic, the observer only receives radiation from within the relativistic cone of angular size $1/\Gamma$, where $\Gamma$ is the bulk Lorentz factor. This cone is centered on, and symmetric with respect to, the line of sight and therefore no polarization is observed. As the expansion slows down, the edge of the relativistic cone reaches the edge of the collimated beam and thereafter looks asymmetric to the observer. A net polarization arises, that reaches a maximum as the relativistic cone expands and looks more and more asymmetric, and drops to zero again when the emitting areas contributing to the polarization in two different directions ("vertical and horizontal") become equal. The polarization then rises again with increasing asymmetry between the areas emitting the two possible polarization directions, but with the position angle rotated by 90°. The polarization finally drops to zero again when $\Gamma \to 1$ (GL99), or exhibits a third maximum if the jet is spreading (S99).

In Figure 1a we show a typical evolution of the polarization for a conical beam of fixed opening angle, $\theta_c = 5^\circ$, with the observers line of sight making an angle $\theta_0 = f \theta_c$, ($f < 1$), with the cone symmetry axis. We used the approach of GL99 to construct the figure and therefore only exhibit two maxima. The evolution is shown as a function of the inverse bulk Lorentz factor for two different values of $f$. The Lorentz factor can be converted to time, using the relation $\Gamma = \Gamma_0 (t/t_0)^{-3/8}$. For this figure we have used $\Gamma_0 = 100$ for the initial value of the Lorentz factor and $t_0 = 50$ s. Note that lowering $f$ for a fixed $\theta_c$, brings the observers line of sight closer to the symmetry axis and therefore decreases the net polarization. It also shifts the first maximum and the minimum to later times (lower $\Gamma$), while the second maximum occurs almost at the same time ($\Gamma \approx 5$). Note also, that the first maximum occurs typically less than an hour after the burst, the minimum less than 10 h after the burst and the second maximum from 1-2 days after the burst. The polarization level is modestly affected by the radiation spectral index. We assume a power law spectral distribution, and take the spectral index to be $\beta = 0.6$ as e.g. observed for GRB 990712
A crucial effect that is not discussed in detail by GL99 and for which S99 considers only one particular example in his toy model, is the evolution of \( f \), the ratio of the angle the line of sight makes with the jet axis to that of the collimated beam. The jet axis is most likely defined by the angular momentum of the burst progenitor system, and is presumably fixed in space. The angle between the jet axis and the line of sight should therefore be constant, unless the jet is precessing for which there is no evidence. If the jet is expanding laterally, the ratio \( f = \theta_0/\theta_c \), decreases with time. Generating a sequence of polarization curves as in Fig. 1a, varying (increasing) only the jet opening angle, shows a decreasing magnitude of both maxima and a shift of the first maximum and the minimum to the right (towards lower \( \Gamma \) or later times). The evolution of the second maximum is particularly interesting as it takes place entirely under the polarization curve defined by the initial value of \( f \), with the maximum occurring at almost constant value of \( \Gamma \) (see also S99 and GL99).

We show an example in Figure 1b, with the data points of GRB 990712 superimposed. As the first data point is obtained about 11 h after the burst, we assume that the polarization at that time has already evolved into the region of second maximum and therefore that the position angle has already changed by 90°. With \( \Gamma_0 = 100 \), and \( t_0 = 50 \) s, we find that an opening angle of \( \theta_c = 5.1° \pm 0.1° \), with \( f = 0.9 \), fits the first point. We then let \( \theta_c \) increase to \( 6.0° \pm 0.2° \), over the next 6 h, giving \( f = 0.77 \), and finally a modest increase to \( 6.2° \pm 0.5° \) fits the last point 18 h later. The last two data points are also consistent with being on the same polarization light curve. In that case we would be observing a widening of the collimation angle by 1° over a 6 h period between the first and the second point, and approximately a constant opening angle thereafter, or a slower rate of lateral expansion that may be due to density irregularities in the local environment. We emphasize that the above is obtained by taking “snapshots” of the evolving polarization light curve, where only
the jet opening angle has been changed between each shot. The “error estimates” on the opening angle are determined by searching for values of \( \theta_c \) that give polarization within the error of the measured polarization points at the appropriate time. It is interesting that a modest variation in the jet opening angle (about 20\%), can easily change the polarization by a factor of two to three. An important consequence of the variable polarization being due to temporal evolution of the second maximum is a constant position angle, naturally explaining the observations of the GRB 990712 afterglow.

The above analysis is a simple extension of the GL99 model, and complements the approach of S99 that assumed that the jet opening angle evolved as \( 1/\Gamma \), once \( \Gamma \) had decreased below the inverse of the initial jet opening angle. The initial polarization evolution, i.e. the first maximum and minimum, is therefore similar in both approaches, differences arising when the jet opening angle starts spreading, but the polarization light curve at that time is already in the region of second maximum. Despite differences in details of GL99 and S99, the location of the the second maximum in both cases occurs on similar time scales, about 1-2 days after the burst. We have shown here that a modest variation in the jet opening angle is sufficient to explain the polarization measurements of Rol et al. (2000). Numerical simulations using more realistic models are needed to follow the detailed temporal evolution of the polarization light curve, in particular the evolution of the second maximum.

The optical light curve of GRB 990712 decayed as a power law with an index of \( \alpha \approx -1.0 \) (Sahu et al. 2000, Hjorth et al. 2000). This is similar to the decay index of GRB 990123 and somewhat steeper than that of GRB 990510, before the break in their light curves. In the latter two cases the light curve steepened about 1-2 days after the burst (e.g. Kulkarni et al. 1999; Harrison et al. 1999; Stanek et al. 1999; Israel et al. 1999; Holland et al. 2000). A model of a collimated outflow predicts a steepening of the light curve
when $1/\Gamma \approx \theta_e$, the sharpness of the break depending on the rate of lateral expansion (e.g. Rhoads 1999), and the break in the light curves of GRB 990123 and GRB 990510 indicates a jet opening angle of about 5°. Interpreting the polarization data for GRB 990712 with a spreading jet, therefore implies that the optical light curve should show a break after about 1-2 days. The modest increase in the opening angle implied by the polarization measurements requires the break to have been rather sharply defined in time. No such break has been reported (Sahu et al. 2000; Hjorth et al. 2000), perhaps because the host galaxy is bright and was already affecting the magnitudes of the optical transient 10 h after the burst (second data point on the optical light curve).

The polarization measurement of GRB 990123 at 18.3 h and of GRB 990510 at 18.5 h, 20.7 h and 43.3 h, are likely to have been taken during the second maximum. It is crucial that polarization measurements be attempted as soon as possible after the discovery of an optical afterglow. In particular, to demonstrate the 90° change in the position angle, a positive detection well before a burst age of 10 h is needed and would nicely confirm the applicability of collimated models. A well sampled polarization light curve is a powerful tool in exploring the properties of burst afterglows and their surroundings and can potentially provide more detailed information than the optical light curve alone.

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Fig. 1.— a) Typical evolution of the polarization light curve for constant $\theta_c = 5^\circ$, and $f = 0.9$ (solid curve) and $f = 0.67$ (dotted curve). Note that the first maximum and the minimum shifts to the right as $f$ is decreased, while the second maximum only decreases in amplitude. b) Polarized light curves of a collimated outflow with a varying opening angle and a fixed angle between the jet symmetry axis and the line of sight. If $\theta_c$ is increased, $f$ decreases. The solid curve has $\theta_c = 5.1^\circ$ and $f = 0.9$, the dashed has $\theta_c = 6.0^\circ$ and $f = 0.77$, and the dotted has $\theta_c = 6.2^\circ$ and $f = 0.74$. As in panel a), the first maximum and the minimum move to the right while the second maximum shifts to the right by a factor of 2 in time but does not cross the initial curve (solid). The polarization values for GRB 990712 are superimposed. We have assumed that the maximum polarization from synchrotron radiation is $P_0 = 70\%$, in both a) and b).