Polarization in the prompt emission of gamma-ray bursts and their afterglows

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New Journal of Physics 8 (2006) 131
Received 16 May 2006
Published 7 August 2006
Online at http://www.njp.org/
doi:10.1088/1367-2630/8/8/131

Abstract. Synchrotron radiation is considered the dominant emission mechanism in the production of gamma-ray burst photons in the prompt as well as in the afterglow phase. Polarization is a characteristic feature of synchrotron radiation and its study can reveal a wealth of information on the properties of the magnetic field and of the energy distribution in gamma-ray burst jets. In this paper, I will review the theory and observations of gamma-ray burst polarization. While the theory is well established, observations have proven difficult to perform, due to the weakness of the signal. The discriminating power of polarization observations, however, cannot be overestimated.

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1. Introduction

The ‘standard’ model to interpret gamma-ray burst (GRB) emission implies dissipation of bulk kinetic energy via collisionless shocks [1]–[3]. Magnetic fields are generated in the process and highly relativistic electrons are accelerated in a power-law distribution of energies (or Lorentz factors) [4, 5]. Under these conditions, synchrotron radiation is produced, giving rise to a broad band radiation source [3, 6].

Synchrotron radiation from a coherent magnetic field is known to be polarized. As a consequence, theoretical and observational efforts were produced to understand if and how much polarization should be observed in the various phases of the GRB process. In this paper we divide the GRB into two distinctive phases, the prompt and the afterglow. For each phase we consider both theoretical predictions for linear polarization (circular polarization is supposed to be very small, especially in the afterglow phase [7]) and observations. In both cases we will emphasize how the understanding of the polarization properties of GRBs can shed light on other important issues such as the release mechanism of GRB jets, the micro-physics of collisionless shocks, the energy distribution of jets and the properties of dust along the line of sight to the GRB.

2. The afterglow phase

Even if the afterglow phase follows the prompt phase in GRB observations, it is worth discussing (and historically more correct) the polarization of the afterglow emission before the polarization of the prompt phase. This is due to the fact that the synchrotron nature of afterglow photons is more firmly established and widely accepted, compared to the highly debated origin of the prompt emission. For this reason, theoretical predictions of linear polarization in the afterglow phase appeared earlier than those related to the prompt emission. As we shall see in the following, the prompt emission polarization has, however, a greater potential to reveal the nature of GRBs than that of the afterglow phase.

In order to discuss the polarization properties of synchrotron radiation, we must first address the geometry of the magnetic field that we expect in the afterglow. In the standard model, the afterglow magnetic field is generated in the collisionless shock driven by the fireball in the interstellar medium. Amplification of the interstellar magnetic field just due to the shock compression is not sufficient to generate a magnetic field large enough to explain the observed afterglow spectra and luminosities.

Numerical particle-in-cell (PIC) simulations of collisionless shocks have become available only in recent years. The computing volume is still small and only several tens of skin depths can be followed (a tiny fraction of the plasma volume is supposed to be involved in the afterglow production). Nevertheless, the two stream instability (Weibel instability [8]) seems to be able to generate fields close to equipartition that, within the explored volume, do not decay due to diffusive dissipation [9]–[11]. Analogously to compressed fields, such fields are tangled in the plane of the shock but show a remarkable degree of alignment if observed orthogonally to the normal of the shock plane [12]. Whether these fields are capable of surviving in the bulk of the shocked fluid, which is many orders of magnitude larger than the volume explored in simulations, is still a matter of open and lively debate.

Linear polarization in GRB afterglows can be produced in at least two ways by such fields. Gruzinov and Waxman [13] discussed the possibility of creating coherent patches of magnetic
field within the visible area of the fireball by reorganizing the shock-produced field. They found that these patches can grow and linear polarization at the level of

\[ P = \frac{70\%}{\sqrt{N}} \sim 10\% \quad (1) \]

is expected, where \( N \sim 50 \) is the expected number of visible domains. The process is stochastic in nature and therefore a straightforward prediction of the model is that polarization should be subject to erratic variations of the position angle on timescales \( \delta t \sim T \), where \( T \) is the time since the burst explosion. The amplitude of polarization should also fluctuate on top of a decreasing trend, due to the increase in the number of visible patches. The strong variability of position angle is due to the fact that any new magnetic domain that enters the visible area can completely shift the polarization vector. Observations of linear polarization in optical afterglows seem to fail to detect such an erratic behaviour, but see below for a more thorough discussion.

The discovery of achromatic breaks in the afterglow decay of most GRBs yielded the conclusion that most GRBs are not spherical explosions but collimated outflows. Polarization from a jet observed at an angle from its symmetry axis can be detected even if the magnetic field is completely tangled within the plane of the shock \([8, 14, 15]\), provided that it has the planar structure described above. To understand this, let us first consider the effects of the aberration of light in an expanding fireball. As a consequence of the relativistic aberration of photons only a small fraction of the fireball is visible. To be more precise, if the fireball is uniformly luminous in the comoving frame, \( \Sigma_1 = \pi R^2 / \Gamma^2 \) (2), where \( R \) is the fireball radius and \( \Gamma \) its Lorentz factor. Figure 1 shows a simulated image of a fireball expanding at constant Lorentz factor \( \Gamma = 10 \) and radiating uniformly a flat featureless spectrum. The white dashed line shows the edge of the fireball while the red circle shows the region in equation (2). Consider now photons coming from the red circle in the figure. In the comoving frame, they are produced in a direction orthogonal to the shock. They see therefore a very coherent magnetic field and are highly polarized in the direction parallel to the shock velocity. In the observer frame, they are boosted in a direction that forms an angle \( 1 / \Gamma \) with the shock velocity. The polarization vector (the electric vector) is rotated accordingly. Due to the shape of the synchrotron spectrum, to the rapid variability of the brightness, and to light travel effects (all not considered in figure 1), the observer at infinity sees a ring shaped source \([17, 18]\) at the position of the red circle in the image. The radiation from the ring is highly polarized in the local radial direction (relative to the centre of the image). If the observer could resolve the ring, polarization would be observed. Unfortunately, the observer sees the integrated radiation from the circle and different polarization directions cancel out.

An additional ingredient to this scenario is provided by the collimation of jets. Consider an observer located slightly off-axis a collimated outflow \([14, 15]\). He sees radiation coming from a circle centred on the line of sight. At early stages, the radiation comes from a small ring uniformly illuminated and no polarization is observable. As time goes on and the fireball slows

\(^1\) Note here that there is not a single ‘fireball comoving frame’. Since the fireball is expanding radially, each point in the fireball defines its own comoving frame in which every other part of the fireball is moving.
Figure 1. Image of a relativistic fireball expanding with a constant Lorentz factor \( \Gamma = 10 \) and with a uniform luminosity (and flat spectrum) in the comoving frame. The white dashed line shows the edge of the fireball, while the red circle shows the region from which half of the photons are observed (see equation (2)). The luminosity of the fireball is supposed to be also constant in time, so that the light travel time effects are irrelevant.

As the fireball slows down, the size of the ring increases and, eventually, one side of the ring hits the edge of the jet. From this moment on, polarization will not cancel out completely. Ghisellini and Lazzati [14] and Sari [15] independently derived polarization curves for this scenario. A schematic view of this process is shown in figure 2. The polarization is expected to be vanishing at very early times, since the whole ring is inside the fireball when the Lorentz factor is very high (upper left panel). As the fireball slows down, the ring from which most of the radiation is emitted grows until its lower part is located outside of the fireball (upper right panel). In this configuration, some vertical polarization is missing and therefore a net horizontal polarization is observed. At some point, exactly half of the ring is inside the fireball (the grey circle) and half of it is outside. In this configuration (lower left panel) the two components of polarization balance again and no net polarization is observed. Finally, as the emission ring becomes larger and larger, only a small upper portion is inside the fireball and all the polarization becomes vertical.

This simple scenario can be complicated by taking into account the lateral expansion of the jet [15]. Polarization curves have been computed, since the model was originally proposed, with increased refinement. Figure 3 shows the results obtained using the code of Rossi et al [19]. It was eventually shown that even though the lateral expansion of the jet can modify the polarization curve, it does not affect its general behaviour and especially the presence of the sudden rotation by 90° of the position angle approximately in concidence with the steepening in the light curve [19, 20].
Figure 2. Cartoon explaining the behaviour of polarization from a shock-generated magnetic field in a collimated outflow. The grey circle shows the fireball seen face on. The asterisk in the lower centre of the circle shows the location of the line of sight. Time runs from left to right and from top to bottom. The coloured rings with arrows show the location of the photon producing rings. The whole ring (blue) is initially inside the fireball and no polarization is seen. At later times, the lower part of the ring is lost and horizontal polarization is detected (red). Finally (orange ring) only the top part of the ring is seen and vertical polarization is detected. These two parts are separated by a moment of vanishing polarization when only half of the ring is visible (magenta).

After the discovery of polarization in GRB990510 [21, 22], polarimetric observations in search for the position angle rotation have been performed in a number of bursts. Observations of good quality have been obtained for GRB 021004 [23], GRB 020813 [24] and GRB 030329 [25] (see Covino et al [26] for a complete review of polarization observations in GRB afterglows). For the case of GRB 021004, it was initially claimed that the 90° rotation had been detected. However, it was subsequently shown that the rotation had been observed at time earlier than expected [27]. The rotation of the position angle is supposed to be roughly coincident with the time at which the jet geometry produces a steepening in the afterglow light curve [15, 28]. In the case of GRB 021004 it was observed an order of magnitude earlier in time [27]. In addition, a progressive change was observed rather than a sudden one. A possible explanation for the strange behaviour of the polarization angle of GRB 021004 is that its fireball was not uniformly bright. The presence of prominent bumps in its light curve [29] is suggestive of such a case. If the fireball is not uniformly bright, then the polarization component of the bright spots dominates over the rest [20, 27, 30]. The polarization during flares can therefore be larger and show a
Figure 3. Polarization curves from a top-hat jet with shock-generated magnetic field. Different colours show polarization for different viewing angles in units of the jet opening angle. All curves but the one with $\theta_o = \theta_j$ have two polarization peaks. The polarization angle in the two peaks is rotated by 90°. The black curve has only one peak that has the same orientation of the second peak of the other curves.

random orientation of the position angle. Additional modifications of the polarization curve can be due to the propagation of the afterglow photons in the interstellar medium (ISM). Dust grains are dichroic and bi-refringent and induce polarization (and/or rotate the intrinsic one, if any [27]). Local dust induced polarization is however easy to disentangle from the prompt one with a suitable set of observations. It has a well-known spectral dependence and is constant in time. High redshift dust induced polarization is not well known. It is expected that it should be less severe (for a given amount of dust) since the grains are expected to be smaller (the extinction curves are often analogous to SMC templates). GRB afterglow spectropolarimetry is a great tool to study high redshift dust. Unfortunately, so far no induced polarization has been detected, probably due to the unavoidable bias that associates induced polarization with extinction.

A more fortunate case is that of GRB 020813. This GRB had the smoothest light curve measured so far, with stringent limits on its variability (on top of the regular broken power-law behaviour) [31]. Polarization measurements were performed with good signal to noise before and after the jet break, an ideal sample to check for the presence of the 90° rotation of the position angle. The modelling of the data showed that no rotation was present, ruling out for this event a simple top-hat jet configuration with shock-generated magnetic field [24]. Either the structure of the jet or of its magnetic field have to be different than what postulated in the simplest scenario. Polarization from structured jets (with bright cores and dimmer wings) was computed by Rossi et al [19]. In this configuration, for a shock generated magnetic field, the polarization position angle is always towards the brightest part of the jet and therefore no rotation of the
Figure 4. The light curve, linear polarization and position angle of GRB 030329. The top panel shows the R-band light curve [32] of GRB 030329 after the subtraction of a power-law model. This emphasizes the presence of bumps and wiggles on top of the regular power-law decay. The central panel shows the linear polarization data and the bottom panel shows the relative position angle [25]. Grey shadowed regions are overlaid to emphasize the connection between the light curve bumps and the time at which polarimetry was performed.

position angle is expected. In addition, differently from what is expected in top-hat jets, the polarization has a maximum at the jet break time rather than a minimum. Alternatively, it can be assumed that the magnetic field has some degree of order, and is not entirely shock generated. In this case the orientation of the magnetic field dominates the position angle behaviour that is, again, constant. However (see also below for the case of the prompt polarization) if the magnetic field is ordered, a large polarization at early times is expected, contrary to any model in which the field is shock-generated [20, 24]. The data of GRB 020813 are consistent with either scenario. In no case the polarization has been observed at times early enough to allow us to disentangle the effect of the jet structure from the effect of the field orientation.

The afterglow with the best polarimetric sampling is, beyond any reasonable doubt, that of GRB 030329 [25]. Linear polarimetry (and even spectro-polarimetry) were performed at many times (see figure 4). Unfortunately, the light curve of GRB 030329 is one of the least smooth,
with variability overlaid on very short timescales [32]. The origin of this variability is not yet clear, but it is beyond doubt that it must involve a region on the fireball surface that is smaller than the one causally connected since the flares rise time is much shorter than the curvature time scale [29]. A flaring event on a small portion on the fireball surface could produce such variability. Alternatively, rapid variability can be produced by an event involving the whole fireball after the jet break time, if the fireball does not spread to fill the whole causally connected area. In such conditions it is very hard to predict the behaviour of polarization. The most interesting feature in figure 4 is the change in the trend of the position angle evolution during the first set of measurements around 0.6 days after the explosion. In this range of time the light curve is smooth, the polarization is uniformly decreasing, yet the position angle trend has a break. Such a behaviour is not easy to interpret in any of the theoretical frameworks outlined above. Being a single case it is possible to argue that it is a coincidence, and indeed it is possible that a non-uniformly bright fireball produces a smooth light curve, a smooth polarization curve and yet has random position angle variations [30].

In summary, the theory of afterglow polarization is well developed. Observations have however proven difficult, and the few cases in which a good sampling of the polarization curves has been obtained are related to peculiar events, for which no clear conclusion can be obtained. It is not yet possible to understand whether the theory is on the right track or not. Crucial observations at very early stages and a dense polarization sampling of a smooth afterglow light curve are still to be performed. The only conclusion we can draw, from the modelling of GRB 020813 [24], is that the simplest jet model fails to explain the observations.

3. The prompt phase

The prompt phase of GRBs is the brightest phase of the phenomenon and is characterized by strong variability and typical photon energies in the hundreds of keV range. These features are thought to be due to the relaxation of instabilities that are injected in the base of the jet, are advected by the flow and reach a catastrophic point at about $R_{\text{IS}} \simeq 10^{14}$ cm from the base of the jet.

The prompt emission is therefore thought to originate from the jet material, interacting with itself (from which the name of ‘internal shocks’). To date, it has been impossible to deconvolve the pulse properties in order to derive physical parameters on the jet properties in the prompt phase. As a consequence, hydrodynamic jet models (e.g., [33]) coexist with fully magnetic models (e.g., [34]) and little is known about the jet launching process, its composition and its dynamics. The synchrotron radiation mechanism itself is highly debated [34]–[36] as well as the dissipation method to convert bulk kinetic energy into thermal energy and eventually radiation (usually identified with relativistic shocks) [37].

3.1. Polarization in the prompt phase

For the reasons highlighted above, any additional information on the prompt phase is extremely important and precious. At the end of 2002 it was announced that the prompt emission of GRB 021206 was linearly polarized to the astonishingly high level of 80% [38]. Even though the detection turned out to be much less robust than initially claimed (see below for a discussion), it stimulated a very intense and productive theoretical effort.
Figure 5. Effect of the relativistic beaming on the geometry of the observed magnetic field. Since only a small area of the fireball can be observed, a toroidal magnetic field permeating the jet can have a large degree of coherence in the visible area.

A first result was the realization that relativistic effects in a spherical (or conical) fireball reduce the observed degree of polarization [20, 34, 39, 40]. This effect is due to the aberration of light. As discussed above, due to the light aberration, only a small portion of the fireball is visible to the observer (see figure 1). This has two effects. On the one hand (see figure 5) the magnetic field appears very well aligned even if the overall structure is more complex. For example, a non-relativistic jet with a toroidal magnetic field seen head-on (or slightly off-axis) is non-polarized. A relativistic jet, instead, has a large degree of polarization, close to the maximum polarization achievable from synchrotron.

A second effect, however, counterbalances this. Consider the zoomed part in figure 5, which represents the visible part of the fireball. The regions of that area close to its edge move with a speed that makes an angle with respect to the line of sight. Due to relativistic aberration, the polarization produced by the edge of the area will be rotated [20, 34]. This causes a net decrement of the observed polarization. This effect affects both the intrinsic and geometric models for prompt polarization.

3.1.1. Intrinsic models. Consider now a structure like the one in figure 5. The fireball jet, that is observed face on in the upper part of the figure, is permeated by a toroidal magnetic field. This is a likely configuration if a sizable magnetic field is advected by the jet from its base. Due to the conservation of magnetic flux, the radial component of the magnetic field will decrease as $B_\parallel \propto R^{-2}$, faster than the orthogonal component $B_\perp \propto R^{-1}$. At large radii (when $\gamma$-ray photons are produced the radius has increased by 5 orders of magnitude or more) only the orthogonal component survives. The bottom part of the figure shows how the magnetic field would appear to an observer that lies away from the jet axis (the singular point of a toroidal magnetic field). Since only a small area is visible, the field is observed as completely parallel.
This is not, however, the only effect of relativistic aberration that plays a role in the polarization of GRB prompt emission. Figure 6 shows the observed magnetic field geometry, as reconstructed by assuming it is orthogonal to the local direction of the linear polarization. The left panel is analogous to the zoomed area in figure 5, where all the field is perfectly aligned. However, the Lorentz boost that connects the different parts of the fireball to the observer is different in the centre of the area from its edges. In particular, the boost at the edges makes an angle with the line of sight direction. This implies an angle rotation of the electric vector and therefore of polarization [20, 34, 39]. The right panel of figure 6 shows how an observer would reconstruct the magnetic field lines by assuming them to be orthogonal to the observed direction of the polarization vector.

An additional ingredient is necessary in order to compute the amount of net polarization resulting after the aberration is taken into account. The local brightness of the fireball depends on the spectral slope since $I(\nu) = \delta^{3+\alpha} I'(\nu')$, where $\delta$ is the Doppler factor and $I(\nu) \propto \nu^{-\alpha}$. As a result, a flatter spectrum will have more flux in the edges of the visible area, and the reduction of polarization will be larger [34, 39]. Figure 7 shows the resulting polarization for a power-law spectrum as a function of the spectral index.

The observations of GRB 021206 showed a very high level of polarization\(^2\) only marginally consistent with the values shown in figure 7. It is possible to envisage scenarios in which the observed polarization could be larger. For example, the intensity distribution of the fireball and the maximum polarization are modified if the pitch angle distribution of the electrons is not isotropic but rather biased towards the orthogonal direction. Some acceleration mechanisms produce such an anisotropic distribution. Figure 8 shows the spectrum and polarization of relativistic electrons with an anisotropic pitch angle distribution, computed following basic synchrotron equations [43, equations (6.23)–(6.26)]. The more anisotropic is the distribution, the larger is the net polarization observed.

3.1.2. Geometric models. In alternative to the models described above, that we called intrinsic, high polarization in the prompt phase can be produced by another class of models, the so-called geometric models [39, 40, 44, 45]. In these models, the polarization would be null in a normal

\(^2\) In the following discussion we will assume the original measurement of polarization is correct [38]. The result has been, however, severely criticized and may not be correct [41, 42].
Figure 7. Resulting polarization of the prompt emission of GRBs from a completely aligned magnetic field as a function of the power-law spectral index. The red line shows the theoretical maximum polarization while the blue dashed line shows the polarization that is observed after light aberration has been taken into account. The result is relevant for the time integrated emission.

geometric configuration, but is enhanced by the simultaneous realization of two conditions. Firstly, the fireball must be very narrow, with an opening angle $\theta_j \sim 1/\Gamma$ where $\Gamma$ is the fireball Lorentz factor. This condition ensures that the Doppler factor for the whole fireball is the same. Secondly, the viewing angle must be such that $\theta_o \sim 2\theta_j$. This condition ensures that the photons that the observer sees are mostly produced parallel to the fireball surface in the comoving frame.

If such geometric conditions are satisfied, high polarization of the prompt emission can be achieved for a shock generated field [46] or if the prompt emission is due to bulk inverse Comptonization of field photons [35, 36]. In the synchrotron case, the polarization is analogous to the afterglow case, but the net result is enhanced by the particular geometric condition that ensures no cancellation takes place due to the different orientations of the field. In the Compton drag case, the geometric conditions ensure that the observer at infinity detects primarily photons that had, in the electron comoving frame, a scattering of $90^\circ$. IC scattering polarize photons as

$$\Pi = \frac{\sin^2 \theta}{1 + \cos^2 \theta}$$

where $\theta$ is the scattering angle. Polarization can therefore locally be complete. Figure 9 shows the resulting polarization as a function of the two geometric conditions outlined above. Polarization can be substantial, but a sizable reduction is always observed even in the more optimistic cases.

The possibility of realizing such strict conditions has been questioned. A posteriori statistics is always difficult to compute. The simultaneous realization of the two geometric conditions is indeed hard, but some circumstances help. The most important one is that GRB 021206 was very bright, even for a moderate redshift. If we assume it lay on the Frail and Amati correlations
Figure 8. Spectra and polarization of an anisotropic distribution of electrons in a relativistic fireball.

[47, 48], it should have had a very small opening angle. This eases largely the constraints on the geometric conditions.

4. In between: polarization of the optical flash

The claimed polarization of GRB 021206 [38] sparked intense theoretic and observational activities. It showed that high-energy polarization is an extremely sensitive tool to explore GRB jet structures and composition. However, it also showed that performing the measurements is very difficult, and a dedicated experiment should be designed. A shortcut may be the observation of polarization from the optical flash [20].

When the fireball impacts on the external medium to produce the external shock, a transient shock is produced inside the fireball itself. This is usually called ‘reverse shock’. The emission from this shock lasts for a short time (the time the shock takes to cross the fireball) and is peaked in the optical. From the polarization point of view, this emission could be similar to the prompt one more than to the afterglow one. The lack of bright optical flashes in the Swift era has so far...
Figure 9. Polarization curves as a function of the observing angle in unit of the relativistic beaming angle. Different curves (see inset) shows polarization from fireballs with different opening angles. The black is the most narrow, while the magenta is the widest.

prevented the observation of very early time polarization. On the other hand, constrains from the radio indicate that the polarization cannot be large [49]. As for the afterglow case, the theory is ready to confront the observations.

Acknowledgments

This review is the outcome of many years of work, shared with many collaborators. I thank in particular G Ghisellini, A Celotti, M J Rees, E Rossi and S Covino for their invaluable help. This work was supported by NSF grant AST-0307502 and NASA Astrophysical Theory grant NAG5-12035.

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