Implications of the Large Polarization Measured in Gamma Ray Bursts

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ABSTRACT

The polarization of the prompt $\gamma$-ray emission has been measured in four bright gamma ray bursts (GRBs). It was nearly maximal in all cases, as predicted by the Cannonball (CB) model of GRBs long before the observations. These results are inconsistent with standard models of GRBs wherein the prompt emission is due to synchrotron radiation. A much smaller linear polarization is predicted by the CB model for the prompt emission in X-ray flashes (XRFs) and in extremely luminous GRBs. These measurements would provide yet another stringent test of the CB model and its unification of GRBs and XRFs.

Subject headings: gamma rays: bursts—polarization: general

1. Introduction

Polarization measurements of radiations from astronomical sources are an important diagnostic tool of their means of production. Gamma ray bursts (GRBs) are not an exception. The polarization of the prompt $\gamma$-ray emission in GRBs can establish the mechanism generating GRBs. Two alternative processes have been discussed as the possible dominant source of polarization of the prompt $\gamma$-ray emission in GRBs: inverse Compton scattering (ICS) and synchrotron radiation (SR). These are the mechanisms underlying the prompt $\gamma$-ray emission in the cannonball (CB) model (Dar & De Rújula 2004 and references therein) and the ‘standard’ fireball (FB) model (see, e.g., Meszaros 2006 and references therein), respectively. In the CB model, the ICS of ambient light by highly relativistic jets naturally results in a sizable polarization, as predicted (Shaviv & Dar 1995; Dar & De Rújula 2004) years before the first GRB polarization measurements were made.
The polarization of the prompt $\gamma$-ray emission has been measured in four bright GRBs: GRB 021206, GRB 930131, GRB 960924 and GRB 041219a. The first measurement, made by Coburn and Boggs (2003) with the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) satellite, found a linear polarization, $\Pi = (80 \pm 20)\%$, of the $\gamma$-rays of GRB 021206. Subsequent analyses by other groups did not confirm this result at the same level of significance (Wiggler et al. 2004; Rutledge & Fox 2004), so that the degree of polarization of GRB 021206 remained uncertain. Later, Willis et al. (2005) have used the BATSE instrument on the Compton Gamma Ray Observatory (CGRO) to measure, for two GRBs, the angular distribution of $\gamma$-rays back-scattered by the rim of the Earth’s atmosphere: $35\% \leq \Pi \leq 100\%$ for GRB 930131 and $50\% \leq \Pi \leq 100\%$ for GRB 960924. Using coincidence events in the SPI (the Spectrometer on the INTEGRAL satellite) and IBIS (the Imager on Board the INTEGRAL satellite), Kalemci et al. (2006) have recently measured $\Pi = 98\% \pm 33\%$ for GRB 041219a. Conservatively, they could not “strongly rule out the possibility that the measured modulation is dominated by instrumental systematics”.

The polarization naturally expected for synchrotron radiation (SR) from electrons that have been shock-accelerated by chaotic magnetic fields is very small. This is unless certain extremely contrived conditions are met, as first proposed (Eichler & Levinson 2003; Waxman 2003; Granot 2003; Nakar, Piran & Waxman 2003; Granot and Königl 2003; Lazzati 2006) after a very large polarization was first detected by Coburn and Boggs (2003). The indications of a nearly maximal polarization in 4 GRBs strongly suggest that there should be a simpler explanation. The observed polarization confirms a simple prediction of the CB model, and further invalidates the standard FB model and other SR-based models, as we proceed to discuss. In the CB model, the predicted linear polarization of the prompt emission in X-ray flashes (XRFs) is nearly an order of magnitude below maximal. Its measurement can be used to test the CB model and its unification of GRBs and XRFs.

2. The polarization of the prompt $\gamma$-ray emission in the CB model

In the CB model (Dar & De Rújula 2000a, 2004), long-duration GRBs and their afterglows (AGs) are produced by bipolar jets of CBs, ejected in core-collapse supernova (SN) explosions (Dar & Plaga 1999). It is hypothesized that an accretion disk is produced around the newly formed compact object, either by stellar material originally close to the surface of the imploding core and left behind by the explosion-generating outgoing shock, or by more distant stellar matter falling back after its passage (De Rújula 1987). As observed in microquasars, each time part of the disk falls abruptly onto the compact object, a pair of CBs made of ordinary plasma are emitted with high bulk-motion Lorentz factors, $\gamma = \mathcal{O}(10^3)$,
in opposite directions along the rotation axis, wherefrom matter has already fallen onto the compact object, due to lack of rotational support. The $\gamma$-rays of a single pulse in a GRB are produced as a CB coasts through the SN glory—the SN light scattered by the SN and pre-SN ejecta. The electrons enclosed in the CB Compton up-scatter glory’s photons to GRB energies. Each pulse of a GRB corresponds to one CB. The baryon number, Lorentz factor, and emission time of the individual CBs reflect the chaotic accretion process and are not currently predictable, but given these parameters (which we extract from the analysis of GRB AGs), all properties of the GRB pulses follow (Dar & De Rújula 2004).

Let primed quantities refer to a CB’s rest system and unprimed ones to the SN’s rest system. In the CB’s system, the bulk of the glory’s photons—or energy $E_i = \mathcal{O}(1)$ eV in the SN rest frame—are incident almost in the direction of relative motion, $\theta'_{\text{i}} = \mathcal{O}(1/\gamma)$. Their energy is $E'_i = \mathcal{O}(\gamma E_i) \ll m_e c^2$, so that their Compton cross section is in the low-energy “Thomson” limit. Let $\theta'$ be the angle at which a photon is scattered by a CB’s electron. It is related to the observer’s angle $\theta$ (relative to the CB’s direction of motion) by:

$$\cos \theta' = \frac{\cos \theta - \beta}{1 - \beta \cos \theta}. \quad \text{(1)}$$

The scattering linearly polarizes the outgoing photons in the direction perpendicular to the scattering plane by an amount (e.g. Rybicki & Lightman 1979):

$$\Pi(\theta') \approx \frac{1 - \cos^2 \theta'}{1 + \cos^2 \theta'}. \quad \text{(2)}$$

Substitute Eq. (1) into Eq. (2) to obtain the value of the (Lorentz-invariant) linear polarization in the observer’s frame. In the large-$\gamma$ approximation, the result is (Shaviv & Dar 1995, Dar & De Rújula 2004; see also the recent work of Lazzati et al. 2004 and Lazzati 2006):

$$\Pi(\theta, \gamma) \approx \frac{2 \theta^2 \gamma^2}{1 + \theta^4 \gamma^4}, \quad \text{(3)}$$

which, for the most probable viewing angles, $\theta \approx 1/\gamma$, is of $\mathcal{O}(100\%)$. This result is easy to understand: For $\gamma \gg 1$, photons viewed at $\theta = 1/\gamma$, i.e., at $\cos(\theta) \approx \beta$, were scattered at $\theta' = 90^\circ$, according to Eq. (1), acquiring a nearly total polarization, according to Eq. (2). In the CB model, GRBs with extremely large equivalent isotropic luminosities are viewed almost on-axis. For them, $\theta^2 \gamma^2 \ll 1$, and their polarization is $\Pi \approx 2 \gamma^2 \theta^2 \ll 1$.

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1The Thomson cross section is $\propto 1 + \cos^2(\theta')$, so that $\theta' \gg \theta'_i \simeq 0$ is an excellent approximation, but for extremely forward-scattering events that do not result in observable photons at GRB energies.

2Some “sociological” aspects of these papers have been discussed in De Rújula (2003).
3. The polarization of prompt $\gamma$-ray emission in the FB models

Synchrotron radiation from a power-law distribution of electrons $dn_e/dE \sim E^{-p}$ in a constant, uni-directional magnetic field can produce a large polarization (e.g., Ginzburg and Syrovatski, 1969; Rybicki and Lightman 1979; Longair 1994), $\Pi = (p + 1)/(p + 7/3) \approx 70\%$, for the canonical power-law index, $p \approx 2.2$. But collisionless shock-acceleration requires highly disordered and time varying magnetic fields (for a recent review see, e.g., Zhang & Meszaros 2003, for a dissenting view, see Lyutikov, Pariev & Blandford 2003). Only under very contrived circumstances, which should be the exception and not the rule—such as geometrical coincidences, and unnaturally ordered magnetic fields—can collisionless shocks produce a large polarization. In our opinion, this is what various articles (Eichler & Levinson, 2003; Waxman, 2003; Granot 2003; Nakar, Piran & Waxman, 2003; Granot and Konigl 2003; Lazzati 2006) on the subject show, although it is not what their authors conclude.

In fireball models, the origin of the prompt and afterglow emissions is synchrotron radiation from mergers (of two fireshells), and from the collision of the ensemble of shells with the interstellar medium (ISM), respectively. No fundamental difference between these collisions is assumed (even though the center of mass energy is larger in the collision with the ISM, implying a larger energy release in the afterglow, in blatant contradiction with the observations). Since a linear polarization is Lorentz invariant, both types of collision should produce a low polarization. Indeed, linear polarizations of the order of a few percent were proposed to arise from causally-connected magnetic patches (e.g. Gruzinov & Waxman 1999), from homogeneous conical jets (Gruzinov 1999; Ghisellini & Lazzati 1999; Sari 1999) and from structured jets viewed off-axis (Rossi, Lazzati & Rees 2002). Small linear polarizations of the optical afterglow have been detected (see e.g. Covino et al. 2005 for a review).

One may argue that, due to relativistic beaming, only a small area of a fireshell merger is visible, and that in such a small patch the magnetic field may be aligned along a single direction. Later, during the afterglow phase, when a larger area becomes visible due to the decreasing Lorentz factor of the relativistic ejecta, the visible area contains many patches with a magnetic field aligned in a random direction, yielding a small total polarization. However, even if the magnetic field were aligned in one direction in the visible patch of a fireshell merger, it is unlikely to be aligned in the same direction in the different fireshell mergers that produce the different peaks of a multi-peak GRB. The time-integrated polarization of a multi-peak GRB, such as GRB 021206, should average to a very small number.

Finally, in shock-acceleration models which invoke synchrotron self-absorption to explain the low-energy spectral shape of GRBs, the linear polarization of self-absorbed SR is small (Ginzburg and Syrovatski, 1969; Longair 1994) $\Pi = 3/(6p + 3) < 20\%$. For a Band spectrum, most of the photons have an energy below the peak energy. If the peak-energy feature results
from self-absorption of the lower-energy SR, the total polarization cannot exceed \( \sim 20\% \).

It may not come as a surprise that SR fails to explain a large polarization of a GRB’s \( \gamma \) rays. It has been known for long that SR fails in accommodating the observed spectrum (Ghirlanda et al. 2004) and that the a-posteriori attempts to explain the ratio of prompt and afterglow total energies (an ‘energy crisis’, Piran 1999) are not convincing.

4. The transition from GRBs to XRFs

The Doppler factor boosting the energy of radiation in the CB’s rest system to the SN’s rest system is:

\[
\delta \equiv \frac{1}{\gamma (1 - \beta \cos \theta)} \approx \frac{2 \gamma}{1 + \gamma^2 \theta^2},
\]

where the approximation is excellent for \( \theta \ll 1 \) and \( \gamma \gg 1 \). In the CB model, XRFs and GRBs are the same phenomenon, viewed from different observer’s angle \( \theta \) (Dar & De Rújula 2000a, 2004; Dado et al. 2004). For GRBs, \( \theta \gamma \sim 1 \), while for XRFs it is larger (Dar & De Rújula 2000a, 2004; Dado et al. 2004). The various GRB and XRF observables scale as powers of \( \gamma \) and \( \delta \). For example, the typical prompt photon energy is \( E_\gamma \propto \gamma \delta \), the spherical equivalent energy is \( E_{\gamma}^{\text{iso}} \propto \delta^3 \), and the peak isotropic luminosity is \( L_p^{\text{iso}} \propto \delta^4 \), implying various correlations between these observables (Dar & De Rújula 2000b, Dado et al. 2006, 2007) and the gradual evolution from the ‘hard’ GRBs to the ‘softer’ XRFs.

For XRFs, Eq. (3) implies a smaller polarization, \( \Pi \approx 2/\gamma^2 \theta^2 \ll 1 \), than for GRBs. For typical XRFs, \( \theta \gamma > 4 \) and \( \Pi \lesssim 12\% \), as shown in Fig. 1. Thus, polarization measurements of the prompt emission in XRFs can provide another crucial test of the CB model and its unification of GRBs and XRFs.

5. Conclusions

A large linear polarization of the prompt \( \gamma \)-ray emission in ordinary GRBs, such as that indicated by data on GRBs 021206, 930131, 960924 and 041219a, provides strong support for the CB model, wherein inverse Compton scattering of ambient light by highly relativistic CBs is the dominant production mechanism of the prompt \( \gamma \)-ray emission. These observations are inconsistent with the expectation from the standard fireball model, wherein synchrotron radiation from shock-accelerated electrons is the assumed production mechanism. The CB model also predicts a small polarization of the prompt emission in XRFs, and in GRBs lying at the upper end of the distributions of peak and equivalent isotropic luminosities. Further
polarization measurements of XRFs and GRBs will provide a decisive test of the CB model unification of these phenomena, as well as extra support to inverse Compton scattering as the dominant source of their prompt radiations.

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Fig. 1.— The linear polarization predicted by the CB model for the prompt emission in GRBs and XRFs as function of $\theta_{\gamma}$. The vertical line $\theta_{\gamma} = 4$ roughly indicates the transition from GRBs to XRFs.