Gamma-ray bursts from alternating-current jets

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ABSTRACT

We propose a gamma-ray burst scenario involving relativistic jets dominated by Poynting flux with alternating toroidal magnetic fields. Such a structure may arise naturally if the jet is formed and powered by the accretion flow in the core of a collapsar. We conjecture that the polarity of the toroidal magnetic field changes randomly due to hydromagnetic turbulence driven by the magneto-rotational instability (MRI), with the typical reversal time determined by the time scale for amplifying magnetic fields up to a dynamically important level. Poynting flux-dominated jets with reversing B-fields provide a natural and efficient way to dissipate energy via the reconnection process. Gamma-rays are produced at the spatially separated reconnection sites. In this scenario, the emergent synchrotron radiation can be highly polarized and can form both smooth and spiky light curves. We note the possibility that cold and dense filaments can form in the reconnection zones as the result of thermal instability. One could then explain the production of very hard X-ray spectra, as due to bound-free absorption of the synchrotron radiation.

Subject headings: gamma rays: bursts — radiation mechanisms: non-thermal — MHD

1. INTRODUCTION

Gamma-ray bursts (GRBs) probably result from the production of ultra-relativistic jets in rapidly rotating, collapsing cores of massive stars (Paczyński 1993). The jets are presumably powered by energy extracted electromagnetically from a rotating accretion disk and/or black hole. A remarkable fraction of the jet energy is dissipated and re-radiated
in the form of gamma-ray bursts, at distances $\sim 10^{13} - 10^{14}$ cm from the core. The most popular models of energy dissipation involve internal shocks, formed via collisions between inhomogeneities propagating down the jet with different velocities (Rees & Mészáros 1994; Sari & Piran 1995). A very high level of velocity modulation at the source, of unknown origin, must be assumed in order to obtain an adequate rate of energy dissipation. The dissipated energy is assumed to be converted efficiently to relativistic electrons, which in turn produce gamma rays by the synchrotron mechanism. These models predict a spectral peak at photon energies consistent with observations (Zhang & Mészáros 2002) and are relatively successful in explaining the observed variety of light curves (Nakar & Piran 2002). However, they are unable to explain the extreme hardness of X-ray spectra that are sometimes observed (Ghirlanda et al. 2003).

The difficulties encountered in modeling very hard X-ray spectra have motivated researchers to study other mechanisms of gamma-ray production. Proposed scenarios include thermal photospheric radiation, thermal multiple Compton scatterings, and Compton scattering by the bulk flow (Lazzati et al. 2000 and references therein). If the polarization measured by the RHESSI satellite (Coburn & Boggs 2003) is real, even if overestimated, then the two former scenarios can be excluded. The bulk Compton mechanism can still work (Begelman & Sikora 1987; Eichler & Levinson 2003; Lazzati et al. 2003), provided that the jet has an opening angle $\leq 1/\Gamma$, where $\Gamma$ is the bulk Lorentz factor.

Another class of GRB models is based on the assumption that the jets are dominated by Poynting flux, even on very large scales (Lyutikov & Blackman 2001; Spruit et al. 2001; Drenkhahn 2002). In these models, energy is dissipated and particles are accelerated via reconnection of the magnetic field. Particularly promising are models in which the polarity of the toroidal magnetic field repeatedly flips. Such a structure can result from flux injection.
by a rotating misaligned dipole (Spruit et al. 2001). In such “striped-wind” models, which were originally proposed to model pulsars (Coroniti 1990), reconnection occurs at the sites of field reversals.

Toroidal field reversals can also arise from the self-consistent evolution of the magnetic field at the base of a jet, according to simulations that follow MRI (magneto-rotational instability) driven accretion. The combination of shear, supported by the differential rotation of the accretion flow, with magnetic turbulence, driven by MRI (Proga et al. 2003), causes the polarity of the toroidal component to change with time (Proga et al., in preparation). Even if a weak poloidal field of given polarity is imposed at the outer boundary, the flow loses memory of this polarity by the time it reaches the inner regions where the jet is formed. The field reversals are stochastic, but the characteristic time scale corresponds to the time scale for winding the toroidal field up to values at which the magnetic pressure becomes strong enough to power an outflow. Consequently, a jet with magnetic reversals is formed. A similar structure, albeit with a different origin, was postulated for AGN jets by Lovelace et al. (1997).

In this letter, we present our preliminary results on GRBs from jets with magnetic reversals. We state the model assumptions and flow parameters in §2.1, and in §2.2 we discuss the production of synchrotron radiation at the photosphere. In §2.3 we investigate the possible formation of sheets or filaments of cold, dense plasma and consider the hardening of the synchrotron spectrum by bound-free absorption. In §2.4 we make predictions about the basic features of the light curves, and in §2.5 we show how X-ray flashes (XRFs) can be unified with GRBs in terms of our model. The main advantages of the model, as well as its uncertainties, are summarized in §3.
2. THE MODEL

2.1. Assumptions and basic parameters

We assume that relativistic jets in GRBs are Poynting flux-dominated, and are composed of magnetic domains with opposite polarities of the toroidal magnetic field. In this model, GRBs are produced following the annihilation/reconnection of magnetic fields at the boundaries between domains. The observed gamma-ray emission comes from the region just downstream of the radius, $R_0$, where the jet becomes optically thin.

The jet is assumed to be conical and uniform in the transverse direction, and can be described by the following parameters: the total energy, $E$; the ratio of the magnetic energy flux to the matter energy flux in the radiating region, $\sigma = L_B/L_M$; the bulk Lorentz factor, $\Gamma$; the opening angle of the jet, $\theta_j$; the GRB lifetime, $t_{GRB}$; the characteristic width of a magnetic domain, $\lambda$; and the ratio of electrons plus positrons to protons $f_e = n'_e/n'_p$.

In jets dominated by the toroidal magnetic component,

$$L_B \approx 2c u'_B \pi (R \theta_j \Gamma)^2,$$

(1)

where $u'_B \approx B'_\phi^2/(8\pi)$ is the magnetic energy density in the jet comoving frame (quantities measured in the jet comoving frame are primed, with the exception of the random electron Lorentz factor). Combining this with the relation

$$L_B = \frac{E_B}{t_{GRB}} = \frac{\sigma}{1 + \sigma} \frac{E}{t_{GRB}}$$

(2)

gives

$$u'_B \approx \frac{1}{2\pi c} \frac{\sigma}{\sigma + 1} \frac{E}{t_{GRB}} \frac{1}{(\Gamma \theta'_j)^2} \frac{1}{R^2}.$$  

(3)

Assuming $n'_e \ll (m_p/m_e)n'_p$,

$$L_M \approx n'_p m_p c^3 (R \theta_j \Gamma)^2,$$

(4)
and noting that
\[ L_M \simeq \frac{E_M}{t_{GRB}} = \frac{1}{\sigma + 1} \frac{E}{t_{GRB}}, \] (5)
we obtain
\[ n_e' = \frac{1}{\pi m_p c^3} \frac{n'_e}{n'_p} \frac{1}{1 + \sigma} \frac{E}{t_{GRB}} \frac{1}{(\Gamma \theta_j)^2} \frac{1}{R^2}. \] (6)

Hereafter, we adopt the following normalizations: \( t_{GRB} = 30 t_{30} \) s; \( \Gamma = 100 \Gamma_2 \); \( \theta_j = 0.1 \theta_{-1} \); \( E = 10^{52} E_{52} \) erg; and \( \lambda = 10^{10} \lambda_{10} \) cm.

### 2.2. Synchrotron radiation at the photosphere

If \( c t_{GRB} \Gamma^2 > R \), the Thomson optical depth for radiation produced within the flow at a distance \( R \) and beamed within the Doppler cone is
\[ \tau_T \simeq \frac{R n'_e \sigma_T}{2 \Gamma}. \] (7)
Combining this with the eq. (6) gives the distance of the photosphere
\[ R_0 \simeq 7.9 \times 10^{13} f_e \sigma^{-1} \Gamma_2^{-3} \theta_{-1}^{-2} E_{52} t_{30}^{-1} \text{ cm}. \] (8)
Inserting eq. (8) into eq. (3) gives
\[ u'_{B,0} = 2.8 \times 10^9 f_e^{-2} \sigma^2 \Gamma_2^4 \theta_{-1}^2 E_{52}^{-1} t_{30} \text{ erg cm}^{-3} \] (9)
and
\[ B'_0 = 2.7 \times 10^5 f_e^{-1} \Gamma_2^2 \theta_{-1} E_{52}^{-1/2} t_{30}^{1/2} \text{ G}, \] (10)
while from inserting eq. (8) into eq. (6) one gets
\[ n'_{e,0} = 3.8 \times 10^{12} f_e^{-1} \sigma \Gamma_2^4 \theta_{-1}^2 E_{52}^{-1} t_{30} \text{ cm}^{-3}. \] (11)

Magnetic energy, released via the reconnection process, is transmitted to the plasma at a rate (per unit surface area)
\[ F'_{in} = u'_{B} v'_{in} \] (12)
where \( v'_{\text{in}} \) is the inflow velocity of magnetized plasma into the reconnection region.

Assuming that the dissipated energy is shared equally among all particles dragged into the reconnection region, the electrons reach Lorentz factor

\[
\gamma_{\text{inj}} = \frac{1}{m_e c^2} \frac{v'_B v'_{\text{in}}}{(n'_e + n'_p) v'_{\text{in}}} = \frac{\sigma (m_p/2m_e)}{1 + f_e} \approx 9.2 \times 10^2 f_e^{-1} \sigma .
\]

These electrons produce synchrotron radiation peaked around

\[
E_{p,0} = \frac{2hc}{3\pi m_e c^2} \gamma_{\text{inj}}^2 \xi_B B_0' \Gamma \simeq 350 \xi_B f_e^{-3} \sigma^3 \Gamma_2^3 \theta^{-1} E_{52}^{-1/2} t_{30}^{1/2} \text{keV} ,
\]

where \( \xi_B = B'_\text{rec}/B' < 1 \) and \( B'_\text{rec} \) is the intensity of the reconnected magnetic field. This formula put constraints on the value of \( \sigma \), which in our model is a free parameter. Noting that typical spectral peak energies in GRBs are \( \sim 300 \text{ keV} \) (Preece et al. 2000), one can conclude that very high \( \sigma \)'s are allowed only for a high pair content \( (f_e \gg 1) \). If the latter is determined by locally \( (\text{in situ}) \) produced pairs, via absorption of synchrotron self-Compton (SSC) photons by synchrotron photons, then \( f_e \) is not expected to be larger than a few. This is because \( L_{\text{SSC}}/L_{\text{syn}} \sim v'_\text{in}/(\xi_B c) \sim 1 \) and pairs are produced in the Klein-Nishina regime. This implies that GRB jets above the photosphere are only mildly dominated by magnetic fields, i.e. \( \sigma \sim \text{a few} \).

Since the time scale of electron synchrotron energy losses,

\[
t_{\text{syn},0} \simeq \frac{3m_e c^2}{4c \sigma \xi_B^2 v'_B \gamma_{\text{inj}}} \approx 2.4 \times 10^{-5} \xi_B^{-2} f_e^{-3} \sigma^{-3} \Gamma_2^{-4} \theta^{-2} E_{52}^{-1} t_{30}^{-1} \text{s} ,
\]

is about 6 orders of magnitude shorter than the dynamical time scale, \( t_{\text{dyn}}' \sim (R/c)/\Gamma \), the electrons cool very rapidly. Steadily injected into a uniform magnetic field, they produce a synchrotron spectrum with a photon index \( \alpha = -1.5 \). Such a spectrum is much softer than that observed in most GRBs (Preece et al. 2002).
2.3. Cold filaments and bound-free absorption?

Several mechanisms have been suggested to make the synchrotron spectra harder, including synchrotron self-absorption (Papathanassiou 1999; Granot et al. 2000), very small pitch angle radiation (Lloyd & Petrosian 2000; originally elaborated by Epstein 1973), and jitter radiation (Medvedev 2001). All of these mechanisms face a variety of difficulties (Ghisellini et al. 2000; Ghirlanda et al. 2003) and none is able to account the hardest spectra observed ($\alpha > 0$). Synchrotron models of GRBs are therefore seriously challenged by observations of extremely hard spectra. There is, however, at least one way to rescue the synchrotron mechanism for GRBs: absorption of synchrotron radiation by very dense and cold plasma sheets or filaments. Such filaments could be formed as follows:

Electrons cooling via synchrotron radiation and the SSC process, and then by thermal Comptonization of the synchrotron radiation, reach the Compton temperature $T'_C \sim 10^8 - 10^9$ K. Protons, very inefficient radiators and very weakly coupled to electrons via Coulomb interactions, might remain mildly relativistic, losing energy only via adiabatic expansion. However, the intense, small scale turbulence likely to be associated with reconnection could well drive plasma instabilities that couple the protons and electrons thermally on much shorter time scales (Begelman & Chiueh 1988; Quataert & Gruzinov 1999). In the latter case, energy would be drained from the protons to the electrons and radiated away (via thermal Comptonization of synchrotron radiation) and protons would also reach the Compton temperature. This cooling can be accompanied by strong compression of the matter along the reconnected magnetic field lines.

Plasma at $T'_C \sim 10^8 - 10^9$ K is unstable to further cooling if the gas pressure is somewhat larger than the ambient radiation energy density (Begelman & McKee 1990). This condition may be satisfied by a factor of a few, depending on the details of flow into the reconnection zone. If it is satisfied, plasma would cool down to temperatures $T'_w \sim 10^4$K,
and would form clouds or filaments with density

\[ n'_w \sim u'_B/kT'_w \sim 3 \times 10^{21} f_e^{-2} \sigma^2 \text{cm}^{-3}. \]  

Under such conditions a significant fraction of the gas is in a neutral state and bound-free absorption of synchrotron radiation can lead to significant hardening of the synchrotron spectrum. Because of neutronization of the plasma in the central region and because only deuterium and \( \alpha \)-particles are recovered by nucleosynthesis during the initial expansion (Derishev et al. 1999; Beloborodov 2003), the absorber is expected to be strongly dominated by HI, HeI and HeII. It is only necessary for \( \sim 1\% \) of the gas in the reconnection region to be in this state in order to provide enough hardening of the synchrotron spectrum in the observed energy ranges. Bound-free absorption hardens the spectrum of synchrotron radiation produced within a mist of a cold gas by \( \Delta \alpha = 3 \). If the intrinsic synchrotron spectrum has \( \alpha = -1.5 \), this would lead to a photon index \( \alpha = 1.5 \).

### 2.4. Light curves

Gamma-ray pulses, produced by individual reconnection sheets, start to build up at \( R = R_0 \) and, due to light travel time effects related to the transverse size within the Doppler beam, reach a maximum after

\[ t_{\text{rise}} \sim \frac{R_0}{2c\Gamma^2} \approx 0.13 \sigma^{-1} t^{1-1} \Gamma^{-5}_2 \theta^{-2}_{-1} E_{52} \text{s}. \]  

After the maximum the pulse decays, partly because the peak of the synchrotron spectrum moves to lower energies with increasing distance \( (\nu_{pk} \propto B' \propto 1/R) \), and partly because of the decreasing efficiency of the reconnection process. (Note, that in the case of reconnection proceeding with a constant rate \( \propto v'_m \approx \xi_A v'_A \approx \xi_A c \), the bolometric flux would last \( \sim \lambda/\xi_A c \) and would start to drop at a distance \( \sim 10^{15} \lambda_{10} \xi_{A,-1}^{-1} \Gamma_2^2 \text{cm} \).) Sequential
pulses are separated by the magnetic reversal time, \( t_\lambda \approx \lambda/c \). The observed rise time and interval between pulses are equal for

\[
\Gamma_c \approx 85\lambda_{10}^{-1/5} f e^{1/5} \sigma^{-1/5} \theta^{-2/5} E_{52}^{1/5} t_{30}^{-1/5}.
\]  

(18)

Thus, for \( \Gamma > \Gamma_c \) the light curves are predicted to be “spiky,” while for \( \Gamma < \Gamma_c \) the light curves are expected to be smooth. This is assuming that all magnetic domains have similar widths. Since we expect a broad distribution of domain sizes, the rise time, for a given Lorentz factor, should define a time variability filter, which suppresses variability on timescales shorter than \( t_{\text{rise}} \). The very strong dependence of the filter scale on the value of \( \Gamma \) provides the new independent method for estimating the bulk Lorentz factor.

2.5. Total energetics and X-ray flashes

As was recently pointed out (Frail et al. 2001; Bloom et al. 2003), the total energetics may be similar for all GRB, and the different luminosities can simply be due to different jet opening angles, i.e., \( L \theta^2 \sim \text{const} \). This, combined with the well-established correlation \( E_p \propto L^{1/2} \) (Lloyd et al. 2000; Yonetoku et al. 2003), suggests that \( E_p \propto 1/\theta \). Our model predicts \( E_p \propto \Gamma^3 \theta \), and therefore can be reconciled with observations if

\[
\Gamma \propto \theta_j^{-2/3},
\]  

(19)

assuming that in all GRBs \( \sigma \sim \text{a few} \).

At present we are not able to verify this relation theoretically, however, we can use it to make a prediction regarding the correlation between short-term variability and the value of \( E_p \). Namely, for larger \( \theta_j \) and, therefore, lower luminosities and lower peak energies, we predict smaller bulk Lorentz factor, and this implies lower variability and smoother light curves (see previous section). The best objects to verify this prediction are XRFs, provided
that they belong to the same class of phenomena as GRBs (Kippen et al. 2002). In these objects $E_p < 30$ keV; therefore, XRFs having the same total energies as GRBs should be of much lower luminosity and produce much smoother light curves than typical GRBs.

3. CONCLUSIONS

Our main results can be summarized as follows:

• Driven by MRI, accretion onto a black hole in a collapsar core may lead to the formation of jets with alternating toroidal magnetic fields;

• Magnetic reconnection at the contact surfaces between domains with opposite magnetic polarities provide spatially separated particle acceleration regions. This provides a natural source of short-term variability in GRBs, without the necessity of imposing rapid, high-amplitude modulations of the jet’s density and speed at its base;

• Under some circumstances, a portion of the plasma in the reconnection sites can condense into a very cold, dense phase. A mist of cold clouds/filaments can harden the synchrotron spectrum via bound-free absorption;

• Our scenario predicts the formation of both smooth and spiky light curves, and provides a method to estimate the bulk Lorentz factor;

• The model can be reconciled with observed correlations between variability, luminosity and spectral peak energy, provided that the bulk Lorentz factor anti-correlates with the jet opening angle. This allows us to make a prediction that the less luminous objects should have smoother light curves. In particular, this prediction applies to XRFs, provided that they represent the same phenomenon as GRBs.

The main uncertainties of the proposed scenario concern the efficiency of the magnetic
reconnection process and the formation of cold and dense gas condensations. Unfortunately, the reconnection process is still not well understood, especially under the extreme conditions of relativistic outflows (Kirk & Skjæraasen 2003), and with rapidly cooling plasmas. The possible occurrence of thermal instability depends critically on such unknowns as the strength and geometry of the magnetic field in the cooling region and the efficiency of energy transport from protons to electrons.

Furthermore, we did not follow the role of pairs in detail. Our preliminary estimates show that SSC photons are effectively absorbed by synchrotron photons, to produce pairs within the reconnection sheets as well as outside. How they will affect the shape of the synchrotron spectrum, and its evolution, is not clear yet. Modeling of pair cascades is also important to provide constraints on the magnetization parameter $\sigma$.

Finally, we note that the creation of cold plasma condensations in our scenario can also provide a basis for bulk Compton models of GRBs. We recall that the plasma is required to be cold in this model in order to provide high linear polarization (Poutanen 1994). It must also satisfy another condition, $\theta_j < 1/\Gamma$ (Begelman & Sikora 1987; Lazzati et al. 2003), the same as for internal shock models (Nakar et al. 2003). Confirmation of high polarization in GRBs, in particular in less luminous objects in which presumably $\theta_j \gg 1/\Gamma$, would be a critical step toward discriminating between the reconnection model and others (Lyutikov et al. 2003).

The project was partially supported by Polish KBN grants 5 P03D 00221, PBZ-KBN-054/P03/2001 and NSF grant AST-0307502. D.P. acknowledges support from NASA LTSA grant NAG5-11736. M.S. and P.C. thank the Fellows of JILA, University of Colorado, for their hospitality.
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