

LINEARLY POLARIZED X-RAY FLARES FOLLOWING SHORT GAMMA-RAY BURSTS

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Received 2005 August 23; accepted 2005 November 9; published 2005 December 6

ABSTRACT

Soft X-ray flares were detected following the short-duration gamma-ray burst GRB 050724. The temporal properties of the flares suggest that they are likely due to the late-time activity of the central engine. We argue that if short GRBs are generated through compact star mergers, as is supported by the recent observations, the jet powering the late X-ray flares must be launched via magnetic processes rather than via neutrino-antineutrino annihilations. As a result, the X-ray flares following short GRBs are expected to be linearly polarized. The argument may also apply to the X-ray flares following long GRBs. Future observations with the upcoming X-ray polarimeters will test this prediction.

Subject headings: accretion, accretion disks — gamma rays: bursts — radiation mechanisms: nonthermal

1. INTRODUCTION

Recently, major breakthroughs were made in our understanding of short-duration gamma-ray bursts (GRBs). The *Swift* satellite made the first localization of a short, hard burst, GRB 050509b (Gehrels et al. 2005), which is proposed to be associated with a luminous elliptical galaxy at $z = 0.225$ (Gehrels et al. 2005; Bloom et al. 2006). A deep search of an underlying supernova has resulted in null results (Hjorth et al. 2005a). Two months later, *HETE-2* localized the second short burst, GRB 050709 (Villasenor et al. 2005), whose optical and X-ray afterglows were detected (Fox et al. 2005; Villasenor et al. 2005). The long-wavelength afterglow counterpart is in a star-forming galaxy at redshift $z = 0.16$, but late-time monitoring again places tight constraints on the existence of a possible underlying supernova (Covino et al. 2005; Fox et al. 2005; Hjorth et al. 2005b). Shortly thereafter, *Swift* localized another one, GRB 050724 (Barthelmy et al. 2005). Being more luminous, its X-ray, radio, optical, and infrared afterglows were all well detected (Romano et al. 2005; Cameron & Frail 2005; Gal-Yam et al. 2005; D’Avanzo et al. 2005). This burst is in an elliptical galaxy at redshift $z = 0.257$ (Prochaska et al. 2005; Barthelmy et al. 2005). The spectral information indicates that the host is again an early-type galaxy, with a stellar population older than ~ 1 Gyr. The overall star formation rate is estimated to be lower than $0.03 M_{\odot} \text{ yr}^{-1}$ (Berger et al. 2006; Barthelmy et al. 2005).

All of the evidence seems to support the suggestion that short GRBs are produced by mergers of two compact objects rather than by collapsar-related events (see Fan et al. 2005 for a general discussion on various models for short GRBs). The commonly discussed scenarios (e.g., Eichler et al. 1989; Paczyński 1991; Narayan et al. 1992; Fryer et al. 1999a) include double neutron star (NS-NS) mergers, mergers between a neutron star and a preexisting black hole of several solar masses (NS-BH), and mergers between a white dwarf and a black hole (WD-BH). The WD-BH scenario is less favored at least for GRB 050509b and GRB 050724, since they are expected to have occurred in star-forming regions and cannot be situated on the outskirts of the host galaxy. Also the disk may be too large to efficiently launch a relativistic jet to power a GRB

(Narayan et al. 2001). On the other hand, NS-NS and NS-BH mergers are expected to occur in early-type galaxies with an old stellar population, and they are expected to occur in regions with a large offset from the host galaxy center (sometimes even at the outskirts of the host galaxy) due to asymmetric kicks during the formation of the NSs (e.g., Bloom et al. 1999). Numerical simulations suggest that the typical coalescence timescale for NS-NS mergers (e.g., Eichler et al. 1989; Narayan et al. 1992, 2001; Davies et al. 1994; Ruffert & Janka 1998; Rosswog et al. 2000, 2003; Aloy et al. 2005) is short, e.g., $t_{\text{acc}} \sim 2.76 \times 10^{-2} \alpha^{-6/5}$ s, where $\alpha \sim 0.1$ is the viscosity parameter (Narayan et al. 2001; Popham et al. 1999). A similar timescale is also derived for NS-BH mergers, although arguments against such a model have been raised recently (e.g., Miller 2005; Rosswog 2005). Nonetheless, the host galaxy identifications and the observed short durations of the hard spike in these GRBs are generally consistent with the merger models, especially the one involving NS-NS mergers.

Here we stress an important new phenomenon, i.e., the soft X-ray flares (lasting for a few hundred seconds or even longer) detected in GRB 050724. We argue that the flares are ejected directly from the central engine and should be of magnetic origin. The emission in the flares should therefore be linearly polarized.

2. X-RAY FLARES FOLLOWING THE SHORT, HARD GRB 050724

The prompt emission (15–25 keV) of GRB 050724 contains two emission components, a short, hard pulse followed by a long, soft emission component lasting longer than 100 s (see Fig. 1b of Barthelmy et al. 2005). The long-soft emission component is spiky. This is confirmed by the *Swift* X-ray Telescope (XRT) observations starting from 79 s after the trigger, which overlap the Burst Alert Telescope (BAT) observation of the soft component. The early XRT light curve initially shows a steep decay, with a slope ~ -2 . This flarelike event is then followed by a very rapid decay after ~ 100 s (the index of the power-law decay ~ -10). Around 200–300 s, a second, less energetic flare emerges. The X-ray flux drops rapidly again (with index -7) between 300 and 400 s and then flattens (see Fig. 3 of Barthelmy et al. 2005).

Previously, the temporal variabilities in some GRB afterglows have been interpreted as being due to refreshed external shocks (e.g., Granot et al. 2003 for GRB 030329). In such a scenario, the light curve after each “refresh” is boosted and the light curve typically shows a “steplike” behavior (e.g., Zhang

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& Mészáros 2002a). The decay slope in any external shock model can not be steeper than $-(2 + \beta)$ (where β is the spectral index of the emission), a limit set by the so-called “curvature effect” (Kumar & Panaitescu 2000; see also Fan & Wei 2005 and Panaitescu et al. 2005 for derivations). The observed very steep decays (with indices -10 and -7) following the two flares are therefore not consistent with such an interpretation.

Alternatively, the flares may be the consequence of the late central engine activity, as has been extensively discussed recently (e.g., Fan & Wei 2005; Burrows et al. 2005; Zhang et al. 2005). In this scenario, if the central engine operates in well-separated episodes, a steep decay can be expected to follow the end of each episode. After the central engine turns off, the tail emission should decline as $\sum_i F_{\nu_X, i} [(t - t_{\text{ej}, i}) / \delta t_i]^{-(2+\beta_i)}$, where i represents the i th pulse, $F_{\nu_X, i}$, $t_{\text{ej}, i}$, and δt_i are the peak flux, the ejection time, and the variability timescale of the i th pulse, respectively. By choosing the trigger time as the zero point, the decay slope after a late-time flare could be in principle (much) steeper than $-(2 + \beta)$ (Fan & Wei 2005; Zhang et al. 2005).

So the “X-ray flares” following GRB 050724 are likely produced by the operation of the central engine (see also Barthelmy et al. 2005; Zhang et al. 2005). However, in the standard compact object merger scenarios, it is a big challenge to prolong the accretion episode to as long as a few hundred seconds. One possible model mentioned in Barthelmy et al. (2005) invokes a BH-NS merger system in which the NS may be partially disrupted in the initial collapse. The X-ray flares are produced by the accretion of these late clumps not accreted during the prompt emission epoch. Alternatively, the extended central engine activity may be the result of an accretion flow modulated by the “magnetic-barrier” and gravity (D. Proga et al. 2006, in preparation). MHD simulations show that accretion can be quenched by the strong magnetic field that forms a magnetized polar cylinder (magnetic barrier) around the black hole (e.g., Proga & Begelman 2003). Such a barrier would halt the accretion flow intermittently (see Figs. 6 and 8 in Proga & Begelman 2003), resulting in an episodic accretion rate (see Fig. 3 of Proga & Begelman 2003). This potentially offers a natural mechanism for flaring variability in the magnetic-origin models. Detailed numerical simulations are desirable to validate these suggestions. Here, instead of proposing such a mechanism, we simply assume the existence of such a long-term central engine and turn to investigate the possible energy extraction mechanism that powers the X-ray flares.

3. CONSTRAINTS ON THE ENERGY EXTRACTION MECHANISM

In the compact object merger scenarios (e.g., NS-NS and NS-BH mergers), the total mass available for the accretion is ~ 0.1 – $1.0 M_\odot$. The X-ray flares detected in GRB 050724 lasted ~ 100 s (which is also the timescale of the central engine). Therefore, even if we assume that most of the mass is accreted during the X-ray flare phase rather than during the short, hard spike phase, the time-averaged accretion rate is at most ~ 0.001 – $0.01 M_\odot \text{ s}^{-1}$. This fact alone places important constraints on the energy extraction mechanism near the central engine.

Two popular energy extraction mechanisms have been discussed in the GRB central engine models. Here we discuss them in turn.

Neutrino mechanism.—The first mechanism commonly discussed invokes neutrino annihilation ($\nu\bar{\nu} \rightarrow e^+e^-$; e.g., Ruffert & Janka 1998). The fireball (jet) luminosity driven by this mechanism very sensitively depends on the mass accretion rate,

since the neutrino emission sensitively depends on the density and the temperature of the torus. For accretion rates (\dot{M}) between 0.01 and $0.1 M_\odot \text{ s}^{-1}$, the $\nu\bar{\nu}$ annihilation luminosity could be well fitted by (Popham et al. 1999; Fryer et al. 1999b; Janiuk et al. 2004)

$$\log L_{\nu\bar{\nu}}(\text{ergs s}^{-1}) \approx 43.6 + 4.89 \log \left(\frac{\dot{M}}{0.01 M_\odot \text{ s}^{-1}} \right) + 3.4a, \quad (1)$$

where $a = J_{\text{BH}} c / GM_{\text{BH}}^2$ is the spin parameter of the central black hole and J_{BH} and M_{BH} are the angular momentum and the mass of the central black hole. If one takes the typically value of $a \sim 0.5$ (Fryer et al. 1999b), the jet luminosity powered by neutrino annihilation is $L_{\nu\bar{\nu}} < 10^{45}$ ergs s^{-1} . For GRB 050724, the time averaged isotropic luminosity of the X-ray flare component is $L_X \approx 10^{48}$ ergs cm^{-2} . Since only a fraction of $L_{\nu\bar{\nu}}$ can be converted into the observed X-ray emission, the $\nu\bar{\nu}$ annihilation mechanism cannot provide enough energy to power the X-ray flares detected in GRB 050724, unless the outflow is collimated into a very narrow jet with a solid angle $\Omega < 0.001$ or with a typical jet half-opening angle $\theta_j < 0.03$ rad. Without a proper collimation agent (e.g., a stellar mantle as in the collapsar scenario or a magnetically driven wind from the disk), the outflow resulting from a compact object merger is expected to be only mildly collimated (cf. Guetta & Piran 2005). This viewpoint is also supported by the observations of GRB 050709 and GRB 050724, which implied θ_j -values as large as 0.3 and 0.15 rad, respectively (Villasenor et al. 2005; Berger et al. 2006). We therefore conclude that the neutrino mechanism is insufficient to power the X-ray flares.

Magnetic mechanism.—Alternatively, a relativistic jet could be launched from a black hole–torus system through MHD processes. For example, an MHD numerical simulation for $\dot{M} \sim 1 M_\odot \text{ s}^{-1}$ (Proga et al. 2003) suggests that the efficiency required to convert the accretion luminosity to a Poynting-flux-dominated outflow luminosity is about a factor of $\sim 10^{-4}$ to 10^{-3} (see also Mizuno et al. 2004). Although no specific simulation has been carried out for the parameter range $\dot{M} \sim 0.01$ – $0.001 M_\odot \text{ s}^{-1}$, a natural expectation is that the efficiency should not sensitively depend on the accretion rate, because both accretion and jet formation depend on the same agent, i.e., the magnetic fields in the accretion flow, and because there is no strong dependence on the density and temperature in the torus, as has been noted in the case of neutrino generation. If we still adopt an efficiency of $\sim 10^{-4}$ to 10^{-3} , the expected jet luminosity should be $\sim 10^{47}$ to 10^{48} ergs s^{-1} , adequate for an interpretation of the observed luminosities of the X-ray flares even if a very moderate beaming factor is involved.

Another energy source in the central engine would be the spin energy of the black hole, which might be tapped by magnetic fields through the Blandford & Znajek (1977) mechanism (e.g., Mészáros & Rees 1997). The jet luminosity could be estimated as $L_{\text{BZ}} \approx 2.5 \times 10^{47} (a/0.5)^2 (B/10^{14} \text{ G})^2$ ergs s^{-1} , where B is the magnetic field at the central engine. This power is also adequate to power the X-ray flares as long as the black hole spin energy is essentially not tapped during the prompt emission phase. In such a case, the jet is also Poynting-flux-dominated.

In a Poynting-flux-dominated flow, the observed X-ray flare emission could be due to dissipation of the magnetic fields. By comparing with the pair density ($\propto r^{-2}$, where r is the radial

distance from the central source) and the density required for corotation ($\propto r^{-1}$ beyond the light cylinder of the compact object), one can estimate the radius at which the MHD condition breaks down, which reads (e.g., Zhang & Mészáros 2002b)

$$r_{\text{MHD}} \sim 2 \times 10^{15} L_{48}^{1/2} \sigma_1^{-1} t_{v,m,-3} \Gamma_2^{-1} \text{ cm}, \quad (2)$$

where σ is the ratio of the magnetic energy flux to the particle energy flux, Γ is the bulk Lorentz factor of the outflow, and $t_{v,m}$ is the minimum variability timescale of the central engine. Beyond this radius, significant magnetic dissipation processes are expected to take place (e.g., Usov 1994), which convert energy into radiation. At r_{MHD} , the comoving magnetic fields B_{MHD} can be estimated as (e.g., eq. [13] of Zhang & Mészáros 2002b)

$$B_{\text{MHD}} \sim 50 \sigma_1 t_{v,m,-3}^{-1} \text{ G}. \quad (3)$$

When magnetic dissipation occurs, a fraction ϵ_e of the dissipated comoving magnetic energy would be eventually converted to the comoving kinetic energy of the electrons. Electrons may be linearly accelerated in the electric fields, and we assume that the accelerated electrons have a single power-law distribution $dn/d\gamma_e \propto \gamma_e^{-p}$ for $\gamma_e > \gamma_{e,m}$, where $\gamma_{e,m}$ can be estimated as

$$\gamma_{e,m} \sim 2.1 \times 10^3 \sigma_1 C_p, \quad (4)$$

and $C_p \equiv (\epsilon_e/0.5) [13(p-2)] / [3(p-1)]$. At r_{MHD} , the corresponding synchrotron radiation frequency is

$$\nu_{m,\text{MHD}} \sim 6 \times 10^{16} \sigma_1^3 C_p^2 \Gamma_2 t_{v,m,-3} (1+z)^{-1} \text{ Hz}. \quad (5)$$

The cooling Lorentz factor can be estimated by $\gamma_{e,c} \sim 4.5 \times 10^{19} \Gamma / (r_{\text{MHD}} B^2) \sim 1000$ for typical parameters taken here. This is comparable to $\gamma_{e,m}$. As a result the bulk of the energy of the accelerated electrons is radiated in the soft X-ray band. If this X-ray component due to central engine activity dominates over the forward shock emission component, one gets an X-ray flare.

The dissipation stops abruptly after the reconnection events are over. One then detects a steep decay component due to the curvature effect.

Alternatively, the observed soft X-ray emission could also be due to Comptonization of the mildly relativistic Alfvén turbulence (excited in the wind by reconnection) off the photosphere photons (e.g., Thompson 1994; Mészáros & Rees 2000). If the Lorentz factors of the intermittent outflow are highly variable, internal shocks may still form if σ is not very large. Significant magnetic dissipation at the shock front is needed in order to get a high radiation efficiency (Fan et al. 2004b).

4. LINEAR POLARIZATION OF THE X-RAY FLARES

If X-ray flares are indeed powered by a Poynting-flux-dominated jet, as argued above, a straightforward expectation is that the detected emission should be linearly polarized. This is because the magnetic fields from the central engine are likely frozen in the expanding shells. The poloidal magnetic field component decreases as r^{-2} , while the toroidal magnetic field component decreases as r^{-1} . At the typical radius for “internal” energy dissipation, the frozen-in field is dominated by the toroidal component. For an ultrarelativistic outflow, due to the relativistic beaming effect, only the radiation from a very narrow cone (with the half-opening angle $\leq 1/\Gamma$) around the line

of sight can be detected. As long as the line of sight is off the symmetric axis of the toroidal magnetic field, the orientation of the viewed magnetic field is nearly the same within the field of view. The synchrotron emission from such an ordered magnetic field therefore has a preferred polarization orientation (i.e., the direction of the toroidal field). As a result the linear polarization of the synchrotron emission of each electrons cannot be significantly averaged out, and the net emission should be highly polarized (Lyutikov et al. 2003; Waxman 2003; Granot 2003). The maximum polarization degree in an ordered field could be as high as $\sim(60\%–70)\%$ (e.g., Lyutikov et al. 2003), but a lower polarization degree is also expected, since the dissipation (through magnetic reconnections or internal shocks) process may somewhat break the ordered field and lower the polarization degree (e.g., Granot 2003). Assuming that in the radiation region the strength ratio of the ordered field and the random field is b , the detectable net polarization can be estimated as $\Pi_{\text{net}} \approx 0.6b^2 / (1 + b^2)$ (e.g., Granot 2003; Fan et al. 2004a). It is hard to estimate b without knowing the concrete energy dissipation mechanism. In any case, a global ordered magnetic field component should exist and usually plays an important role. In the magnetic dissipation picture, the observed temporal variability does not have to be related to internal shocks, which would potentially destroy the ordered magnetic field configuration. Rather, the variability is mainly related to the intermittent nature of the accretion flow due to the interplay between the magnetic barrier and gravity (Proga & Begelman 2003). As a result, the ordered magnetic fields generally survive in the dissipation regions.

Measuring polarization is emerging as a new direction for research in high-energy astronomy. New technologies are being invented, and many polarimeter projects are under construction. In the X-ray band, the ongoing projects include the X-ray Polarimeter Experiment (XPE; Elsner et al. 1997), the Stellar X-ray Polarimeter (SXP; Tomsick et al. 1997), the Polarimeter for Low Energy X-ray Astrophysical Sources (PLEXAS; Marshall et al. 1998), and POLAR (Produit et al. 2005), as well as others. For example, the POLAR detector is designed to have an energy range from a few up to several hundred kiloelectron volts and a large field of view, which is very suitable for detecting X-ray flares following short GRBs. An important issue is whether any of these detectors could perform a prompt slew to the short GRBs localized by *Swift* (or other similar GRB detectors). In some cases, weaker X-ray flares happen at an even later epoch (e.g., $>10^4$ s for GRB 050724; Barthelmy et al. 2005). This somewhat eases the urgency of the prompt slew but, on the other hand, requires an even higher sensitivity. An ideal instrument would be an XRT-like detector with a polarization capability on board a *Swift*-like GRB mission.

5. DISCUSSION

We have argued that the X-ray flares detected following the short, hard GRB 050724 should have been linearly polarized if the progenitor of this burst is a compact star merger, as is supported by its association with an elliptical galaxy (Berger et al. 2006; Barthelmy et al. 2005). The argument is achieved through gathering the X-ray flare data and the insights from theoretical modeling of the GRB central engines. Rapid decay following the flares suggests that the flares are not related to afterglow emission. Rather, they reflect the extended central engine activity. Based on the inferred mass accretion rate ($\sim 0.01–0.001 M_{\odot} \text{ s}^{-1}$) from the merger scenarios, the only mechanism available to power the X-ray flares is the one in-

volving magnetic processes, and the jet should carry a dominant ordered magnetic field component. As a result X-ray flares are expected to be linearly polarized. Future X-ray polarimeters may be able to detect the polarized signals from these flares.

Although throughout this Letter we focus on X-ray flares following short GRBs, the main argument may also apply to X-ray flares following long GRBs (Burrows et al. 2005; Piro et al. 2005), although the neutrino mechanism is not cleanly ruled out in that case. Nonetheless, we suspect that those X-ray flares could be polarized as well.

We thank R. Perna for discussions and the referee for helpful comments. This work is supported by NASA under grants NNG05GB67G, NNG05GH92G, NNG05GH91G (for B. Z. and Y. Z. F.), and NNG05GB68G (for D. P.), as well as the National Natural Science Foundation of China (grants 10073022, 10225314, and 10233010) and the National 973 Project on Fundamental Researches of China (NKBRSF G19990754) (for Y. Z. F.).

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