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LETTER

Letter to the Editor

Gamma-ray burst afterglows and evolution of postburst fireballs with energy injection from strongly magnetic millisecond pulsars

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Abstract. Millisecond pulsars with strong magnetic fields may be formed through several processes, e.g. accretion-induced collapse of magnetized white dwarfs, merger of two neutron stars, and accretion-induced phase transitions of neutron stars. During the birth of such a pulsar, an initial fireball available for a gamma-ray burst (GRB) may occur. We here study evolution of a postburst relativistic fireball with energy injection from the pulsar through magnetic dipole radiation, and find that the magnitude of the optical afterglow from this fireball first decreases with time, subsequently flattens, and finally declines again. This may provide a natural explanation for the behavior of the lightcurve of the afterglow of GRB970228 if this burst resulted from the birth of a strongly magnetic millisecond pulsar.

Key words: stars: neutron – pulsars: general – gamma-rays: bursts

1. Introduction

The observational results from the BATSE detector on *CGRO* (Fishman & Meegan 1995) strongly suggested that the sources of gamma-ray bursts (GRBs) are at cosmological distances or in the galactic halo, leading to a great debate on the origin of GRBs. The recent discovery of fading sources at X-ray (Costa, et al. 1997a, b; Yoshida, et al. 1997) and optical wavebands (Groot, et al. 1997; van Paradijs, et al. 1997; Sahu, et al. 1997a, b, c), and the detection of the redshift of the counterpart to GRB970508 (Metzger, et al. 1997), clearly demonstrate that GRBs are at cosmological distances.

Most of the models proposed to explain the occurrence of cosmological GRBs are related with compact objects from which a large amount of energy available for an extremely relativistic fireball is extracted through neutrino emission and/or dissipation of electromagnetic energy. One such possibility is newborn millisecond pulsars with strong magnetic fields, which may be formed by several models, e.g. (1) accretion-induced collapse of magnetized white dwarfs, (2) merger of two neutron stars, and (3) accretion-induced phase transitions of neutron stars. In the first model, an accreting white dwarf, when its mass increases up to the Chandrasekhar limit, may collapse to a rapidly rotating neutron star, and the magnetic field of the neutron star may become very strong due to magnetic-flux conservation (Usov 1992) or efficient dynamo action (Duncan & Thompson 1992). During the birth of the neutron star, an initial fireball may occur through neutrino processes (Dar, et al. 1992) and/or electromagnetic processes (Usov 1992; Yi & Blackman 1997). Second, it is usually thought that a neutron-star binary will eventually merge into a black hole due to gravitational radiation. However, since the equations of state at high densities are likely stiff for several observational and theoretical facts summarized by Cheng & Dai (1997), Dai & Cheng (1997), and Cheng & Dai (1998), neutron-star binaries like the Hulse-Taylor system might merge into massive neutron stars which have both millisecond periods and very strong magnetic fields generated by some physical processes, e.g. dynamo action powered by tidal heating (Vietri 1996). During the coalescence and merging of two neutron stars, an initial fireball may be produced through neutrino-antineutrino annihilation (Eichler, et al. 1989; Mathews, et al. 1997) and/or efficient energy transfer from the orbital energy (Vietri 1996). Third, it has been proposed by Cheng & Dai (1996) that some neutron stars in low-mass X-ray binaries accrete sufficient mass to undergo phase transitions to become strange stars, and after the phase transitions fireballs of GRBs naturally occur from the quark surfaces of the hot strange stars (Cheng & Dai 1996; Usov 1998) because of very-low-mass crusts. The resulting strange stars may have short periods due to accretion-induced spin-up prior to the phase transitions, and they could have strong magnetic fields (Cheng & Dai 1997). Therefore, it can be seen that two common products of these three energy-source models are newborn millisecond pulsars with strong magnetic fields and initial fireballs available for GRBs. Furthermore, Kluźniak & Ruderman (1997) proposed that strongly magnetized neutron stars differentially rotating at

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millisecond periods may be the central engine of gamma-ray bursts.

It is natural to expect that if a GRB results from the birth of a strongly magnetic millisecond pulsar, then after the main GRB the pulsar continuously supplies energy to a relativistic fireball through magnetic dipole radiation. In this Letter we study evolution of the radiation from such a postburst fireball.

2. The model

We assume, as a pulsar is born by the models summarized in the introduction, an amount of energy E comparable to that observed in gamma rays, $E \sim 10^{51}$ ergs, is released over a time interval less than 100 seconds. This initial fireball will expand and accelerate to relativistic velocity because of the huge optical depth in the source (Paczyński 1986; Goodman 1986; Shemi & Piran 1990). Perhaps, internal shocks are formed due to collisions between the shells with different Lorentz factors in this period (Rees & Mészáros 1994; Paczyński & Xu 1994). During the acceleration, the initial radiation energy will be converted to bulk kinetic energy of the outflow. Subsequently, the expansion of the fireball starts to be significantly influenced by the swept-up interstellar medium (ISM) and two shocks will be formed: a forward blastwave and a reverse shock (Rees & Mészáros 1992; Katz 1994). A GRB will be produced once the kinetic energy is dissipated and radiated as gamma rays through synchrotron or possibly inverse-Compton emission from the accelerated electrons in the shocks (Mészáros, et al. 1994; Sari, et al. 1996). The postburst fireball will be decelerated continuously, and an X-ray, optical and/or radio afterglow will be formed, as predicted early by many authors (Paczyński & Rhoads 1993; Katz 1994; Vietri 1997b; Mészáros & Rees 1997).

At the center of the fireball, the pulsar loses its rotational energy through magnetic dipole radiation, whose power is given by

$$L = \frac{2}{3c^3}\left(\frac{2\pi}{P}\right)^4 R^6 B_s^2 \sin^2\theta = 4\times 10^{43}\,\mathrm{ergs\,s^{-1}}\,B_{\perp,12}^2 P_{\rm ms}^{-4} R_6^6\,, \qquad (1)$$

where $B_{\perp,12} = B_s \sin\theta/10^{12}$ G, B_s is the surface dipole field strength, θ is the angle between the magnetic dipole moment and rotation axis, $P_{\rm ms}$ is the period in units of 1 ms, and R_6 is the stellar radius in units of 10^6 cm. This power varies with time as

$$L(t) \propto (1 + t/T)^{-2}\,, \qquad (2)$$

where t is one measure of time in the burster's rest frame, and T is the initial spin-down timescale defined by

$$T \equiv \left(\frac{P}{2\dot{P}}\right)_0 = 5\times 10^8\,\mathrm{s}\,B_{\perp,12}^{-2} P_{\rm ms}^2 I_{45} R_6^{-6}\,, \qquad (3)$$

where $\dot{P}$ is the rate of period increase due to magnetic dipole radiation and I_{45} is the stellar moment of inertia in units of $10^{45}\,\mathrm{g\,cm^2}$. (Note that the stellar spin-down timescale in the burster's rest frame is equal to that in the observer's frame.) For $t < T$, L can be thought as a constant; but for $t \gg T$, L decays as $\propto t^{-2}$.

The power of the pulsar is radiated away mainly through electromagnetic waves with frequency of $\omega = 2\pi/P$. Once the electromagnetic waves propagate in the shocked ISM, they will be absorbed if $\omega_p > \omega$, where ω_p is the plasma frequency of the shocked ISM. Since the electron number density of the shocked ISM in the burster's rest frame is $n_e = 4\gamma^2 n$ (Blandford & McKee 1976), where γ is the Lorentz factor of the shocked ISM and n is the electron number density of the unshocked ISM, for $\omega \sim 10^4\,\mathrm{s^{-1}}$ the inequality $\omega_p > \omega$ is always valid if $n > 0.01\gamma^{-2}\,\mathrm{cm^{-3}}$. This shows that the electromagnetic waves cannot propagate through the shocked ISM and by this means energy can be continuously pumped from the pulsar into the shocked ISM. This idea is similar to that of Pacini (1967), who first proposed that a pulsar can continuously supply energy to its surrounding supernova remnant through magnetic dipole radiation.

In the following we assume that the expansion of the postburst blastwave in uniform ISM is relativistic and adiabatic. At a time t, the shocked ISM energy is given by $E_{\rm sh} = 4\pi r^2 (r/4\gamma^2)\gamma^2 e'$ (Waxman 1997a), where $r \approx ct$ is the blastwave radius and $e' = 4\gamma^2 n m_p c^2$ is the shocked ISM energy density in the comoving frame (Blandford & McKee 1976). This energy should be equal to the sum of $E/2$ and the energy which the fireball has obtained from the pulsar based on energy conservation:

$$4\pi n m_p c^2 \gamma^2 r^3 = \frac{E}{2} + \int_0^t (1-\beta) L(t - r/c)\,dt\,, \qquad (4)$$

where $\beta = (1 - 1/\gamma^2)^{1/2}$ and the factor $1/2$ arises from the fact that about half of the total energy of the initial fireball has been radiated away during the GRB phase (Sari & Piran 1995). The term $(1-\beta)$ accounts for the fact that the fireball moves away from the incoming photons, and the power $L(t - r/c)$ shows the fact that the radiation absorbed by the fireball at time t was emitted at the retarded time $t - r/c$. According to Eq. (2), this power should decrease as $L(t - r/c) \propto [1 + (t - r/c)/T]^{-2} = (1 + t_\oplus/T)^{-2}$, where $t_\oplus$ is the observed time. Because the Lorentz factor of the fireball at the initial evolution stage decays as $\gamma \propto t^{-3/2}$, the timescale in which the fireball has obtained energy $\sim E/2$ from the pulsar can be estimated by $4\gamma^2 E/L$, which is measured in the burster's rest frame. The corresponding observer-frame timescale (τ) is equal to this timescale divided by $2\gamma^2$ (Waxman 1997b), viz., $\tau = 2E/L$. We require $\tau \sim$ 6 days and $T \gg \tau$ for the optical afterglow of GRB970228.

We now analyze evolution of the afterglow from a postburst fireball with energy injection from the pulsar through magnetic dipole radiation. First, at the initial stage of the afterglow, viz., $t_\oplus \ll \tau$, the first term on the right hand of Eq. (4) is much larger than the second term. In this case, one expects that the fireball is not significantly influenced by the stellar radiation, and thus its expansion evolves based on $\gamma = 324 E_{51}^{1/8} n_1^{-1/8} t_\oplus^{-3/8}$, where $E_{51} = E/10^{51}$ ergs, $n_1 = n/1\,\mathrm{cm^{-3}}$, and $t_\oplus$ is in units of 1 second. According to Dai & Lu (1997), therefore, the synchrotron flux (X-ray) integrated between 2 and 10 keV decays as $F_X \propto t_\oplus^{-\alpha_X}$, where $\alpha_X = 3/2 - 3(3-p)/16$, and the synchrotron flux density at some optical band declines as $S_{\rm opt} \propto t_\oplus^{-\alpha_{\rm opt}}$, where $\alpha_{\rm opt} = 3(p-1)/4$. Here p is the index of the power-law distribution of the accelerated electrons in the shocked ISM. The observations of the afterglow of GRB970228 have given $\alpha_X = 1.4 \pm 0.2$ (Costa, et al. 1997a, b; Yoshida, et al. 1997) and $\alpha_{\rm opt} = 2.1^{+0.3}_{-0.5}$ in R band (Galama, et al. 1997). In order to fit these values, we require $p \sim 3$.

Second, for $T > t_\oplus \gg \tau$, according to Eq. (4), the energy which the fireball has obtained from the pulsar is much larger than $E/2$, and the expansion of the fireball is significantly affected by the pulsar's radiation. In the case with steady energy supply, the Lorentz factor of the fireball decays as $\gamma \propto r^{-1/2} \propto t_\oplus^{-1/4}$ (Blandford & McKee 1976). This scaling law can also be found by neglecting the term $E/2$ in Eq. (4). Here we have assumed that the power radiated from the pulsar doesn't vary with time. The comoving-frame equipartition magnetic field decays as $B' \propto \gamma \propto t_\oplus^{-1/4}$, and the synchrotron break frequency drops in time as $\nu_m \propto \gamma^3 B' \propto t_\oplus^{-1}$. At the same time, since the comoving electron number density is $n'_e \propto \gamma \propto t_\oplus^{-1/4}$ and the comoving width of the emission region $\Delta r' \sim r/\gamma \propto t_\oplus^{3/4}$, according to Mészáros & Rees (1997a) and Wijers et al. (1997), the comoving intensity $I'_\nu \propto n'_e B' \Delta r' \propto t_\oplus^{1/4}$. So the observed peak flux density increases in time based on $S_{\nu_m} \propto t_\oplus^2 \gamma^5 I'_{\nu_m} \propto t_\oplus$. Thus, for $\nu \gg \nu_m$, the observed optical flux density as a function of observed time is

$$S_\nu = S_{\nu_m} (\nu/\nu_m)^{-(p-1)/2} \propto t_\oplus^{(3-p)/2} . \quad (5)$$

Therefore, the requirement of $p \sim 3$ inferred from the early-time behavior of the afterglow leads to the result that the observed R-band flux at the subsequent stage may keep relatively constant.

Third, for $t_\oplus \gg T$, the power of the pulsar due to magnetic dipole radiation rapidly decreases as $L \propto t_\oplus^{-2}$, and thus the fireball is hardly influenced by the stellar radiation and the optical flux of the afterglow will significantly decline with time again.

3. Constraints on stellar parameters

The analysis of the lightcurve in the last section can be directly applied to discussion on the afterglow of GRB970228. As pointed out by Galama et al. (1997), the initial decrease of the optical afterglow can be easily explained by the popular fireball model (Mészáros & Rees 1997; Wijers, et al. 1997; Waxman 1997a; Vietri 1997a; Tavani 1997; Reichart 1997; Dai & Lu 1997), but the subsequent flattening is not consistent with this simple model. Further considering the result observed by HST on 4 September (Fruchter, et al. 1997), therefore, we can see that the magnitude of the R-band brightness of the afterglow of GRB970228 first rapidly decreased with time, subsequently flattened, and finally declined again. The lightcurve analyzed in the last section is well consistent with these observational results.

If the afterglow of GRB970228 was radiated from a relativistic fireball with energy injection from a pulsar through magnetic dipole radiation, we now give constraints on some parameters of this pulsar. Inserting Eq. (1) into $\tau = 2E/L$, we get the timescale at which the fireball has obtained energy $\sim E/2$:

$$\tau \approx 5 \times 10^7 \,{\rm s}\, E_{51} B_{\perp,12}^{-2} P_{\rm ms}^4 R_6^{-6} . \quad (6)$$

This equation can be further changed into the following form:

$$B_{\perp,12} \approx 10 E_{51}^{1/2} (\tau/6\,{\rm d})^{-1/2} P_{\rm ms}^2 R_6^{-3} . \quad (7)$$

The R-band magnitude of the optical afterglow during one month following 6 March after GRB970228 didn't vary with time (Galama, et al. 1997), which means that during this period the stellar radiation significantly affected the evolution of the fireball. This in fact requires one condition: $T \geq 36$ days. On the other hand, the V-band magnitude of the afterglow on 4 September dropped to $V = 28.0 \pm 0.25$ which corresponds to the R-band magnitude $R \approx 27.0$ (Fruchter, et al. 1997), showing that for $t_\oplus \gg 1$ month the stellar radiation played no role in the expansion of the fireball. This requires another condition: $T \ll 188$ days. Furthermore, after comparing the observed data with the decay law of the optical flux at the early stage or at the late stage ($S_{\rm opt} \propto t_\oplus^{-3/2}$), we can infer that the flattening phase of the optical flux must have ended around 60 days. This means $T \leq 60$ days. From these conditions and Eqs. (3) and (7), we obtain

$$1.0 \leq P_{\rm ms} E_{51}^{1/2} (\tau/6\,{\rm d})^{-1/2} I_{45}^{-1/2} \leq 1.2 . \quad (8)$$

The equations of state at high densities are likely stiff and thus the moments of inertia of rapidly rotating neutron stars with mass $\geq 1.4 M_\odot$ are $I_{45} \sim 2$ (Datta 1988; Weber & Glendenning 1993). Further adopting $R_6 \sim 1$, $E_{51} \sim 1$ and $\tau \sim 6$ days, we can find $1.4 \leq P_{\rm ms} \leq 1.7$ and $20 \leq B_{\perp,12} \leq 30$. Therefore, we suggest that the central engine of GRB970228 could be a strongly magnetic millisecond pulsar.

4. Discussion

We have studied evolution of a postburst fireball with energy injection from a millisecond pulsar with a strong magnetic field through magnetic dipole radiation if the initial fireball of a GRB has been produced during the birth of the pulsar. In the case of $\tau < T$ or $P_{\rm ms} < 3.2\,{\rm ms} I_{45}^{1/2} E_{51}^{-1/2}$, according to Eqs. (3) and (6), we found that the magnitude of the optical afterglow from this fireball first decreases with time, subsequently flattens, and finally declines again. We have assumed a newborn millisecond pulsar with a strong magnetic field to be an origin of GRB970228, but have not invoked any specific model. There may be several mechanisms relating the birth of strongly magnetic millisecond pulsars with GRBs, e.g. accretion-induced collapse of magnetized white dwarfs, merger of neutron-star binaries, and accretion-induced phase transitions of neutron stars. One expects that one of them could be the mechanism of the birth of a strongly magnetic millisecond pulsar if this pulsar is the central engine of GRB970228. In the case of $\tau > T$ or $P_{\rm ms} > 3.2\,{\rm ms} I_{45}^{1/2} E_{51}^{-1/2}$, the millisecond pulsar as the central engine cannot supply energy to the postburst fireball effectively enough for the flattening phase to occur. It is interesting to note that this feature doesn't depend on magnetic field strength, which influences τ and T in the same way.

We further assume that *some* cosmological GRBs result from the birth of strongly magnetic millisecond pulsars. If the effective dipole magnetic-field strength of a newborn pulsar is extremely high (e.g., $B_\perp = B_s \sin\theta \sim 10^{15}$ G), the stellar rotational energy is dissipated due to magnetic dipole radiation in observed time $T < 10^2$ s. In other words, the fireball of a GRB can obtain a large amount of energy from the pulsar only in such a short timescale. For $t_\oplus \gg T$, thus, the expansion of the postburst fireball is hardly affected by the magnetic dipole radiation of the pulsar. In the superstrong-magnetic-field case, the flattening behavior might not be observable in the optical counterparts of GRBs.

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