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GAMMA-RAY BURSTS FROM NEUTRON STAR KICKS

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ABSTRACT

The idea that gamma-ray bursts might be a phenomenon associated with neutron star kicks was first proposed by Dar & Plaga. Here we study this mechanism in more detail and point out that the neutron star should be a high-speed one (with proper motion larger than $\sim$1000 km s^{-1}). It is shown that the model agrees well with observations in many aspects, such as the energetics, the event rate, the collimation, the bimodal distribution of durations, the narrowly clustered intrinsic energy, and the association of gamma-ray bursts with supernovae and star-forming regions. We also discuss the implications of this model on the neutron star kick mechanism and suggest that the high kick speed was probably acquired as the result of the electromagnetic rocket effect of a millisecond magnetar with an off-centered magnetic dipole.

Subject headings: gamma rays: bursts — neutrinos — pulsars: general — stars: neutron — stars: winds, outflows — supernovae: general

1. INTRODUCTION

Gamma-ray bursts (GRBs), first detected serendipitously in 1967 (Klebesadel, Strong, & Olson 1973), are intense gamma-ray flashes lasting for tens of seconds that occur randomly in the deep sky. The great debate on the distances of GRBs lasted for about 30 yr. The problem was finally resolved in 1997, when X-ray, optical, and radio afterglows from some GRBs were discovered with the successful operation of the Italian-Dutch *BeppoSAX* satellite (van Paradijs et al. 1997; Costa et al. 1997). Observations on GRB afterglows in the past 6 yr have definitely shown that at least most long GRBs are of cosmological origin. Under isotropic assumptions, GRBs would be the most powerful explosions in the universe since the big bang (Kulkarni et al. 1999; Andersen et al. 1999). The famous fireball model, which incorporates internal shocks to account for the main bursts and external shocks to account for afterglows, has become the most popular model (Piran 1999; van Paradijs, Kouveliotou, & Wijers 2000; Mészáros 2002). However, the nature of GRB "central engines" is still far from clear and is still one of the greatest mysteries in modern astrophysics.

Currently, one popular class of "engines" involves the core collapse of very massive stars (heavier than $\sim$40 $M_\odot$), often referred to as hypernovae or collapsars (Paczyński 1998; Fryer, Woosley, & Hartmann 1999). However, core collapse is a very complicated process. Without further careful simulations, it is still largely unclear whether hypernovae and collapsars can successfully generate the required ultrarelativistic ejecta as expected. Another major class of candidates involves the merger of two compact stars, such as neutron star binaries or neutron star–black hole binaries (e.g., Goodman, Dar, & Nussinov 1987; Eichler et al. 1989; Narayan, Paczyński, & Piran, 1992; Bloom, Sigurdsson, & Pols 1999a). But these mergers are usually outside of star-forming regions, and additionally they have difficulties in accounting for the long duration of most GRBs.

In 1999, Dar & Plaga (1999; see also Dar 1999) discussed the possibility that GRBs might come from neutron star kicks. They suggested that the natal kick of a neutron star is due to the emission of a relativistic jet from the compact object. Momentum conservation then indicates that the kinetic energy enclosed in the jet is $\sim 4 \times 10^{51}$ ergs (Dar & Plaga 1999; Dar 1999), enough to account for typical GRBs. Largely on the basis of this assumption, they have proposed the cannonball model of GRBs (see Dado, Dar, & De Rújula 2002a and references therein).

In this research we study the energy mechanism suggested by Dar et al. in more detail. We show that the model naturally meets many of the requirements imposed by GRB observations. We especially point out that the neutron star in this model should be a high-speed one ($>$1000 km s^{-1}), which probably receives the large kick velocity through the electromagnetic rocket effect.

2. MOMENTUM CONSERVATION

Observations of GRBs and their afterglows have provided useful clues about the nature of GRB central engines. In the currently popular models of GRBs, the central engine must satisfy the following requirements: (1) The central engine should release an isotropic-equivalent energy of $\sim 10^{51}$–10^{53} ergs. (2) The energy release should usually be highly collimated, with typical half-opening angle of $\theta \sim 0.1$ rad (e.g., Frail et al. 2001). (3) There should be very few baryons in the beamed ejecta, so that it can move ultrarelativistically with a bulk Lorentz factor of $\gamma \geq 100$–1000 (Lithwick & Sari 2001). (4) The progenitors should be embedded in star-forming galaxies and should follow the cosmic star formation rate (Wijers et al. 1998; Fruchter et al. 1999). In fact, there is accumulating evidence that long-duration GRBs are associated with Type Ic supernovae (Kulkarni et al. 1998; Galama et al. 1998; Bloom et al. 1999b; Reeves et al. 2002). Recent good evidence for this GRB-supernova connection comes from the observations of afterglows from GRBs 020405 and 030329 (Price et al. 2003; Masetti et al. 2003; Stanek et al. 2003). (5) The event rate should be $\sim 10^{-5}$ to 10^{-4} per typical galaxy per year, taking into account the beaming effects. The rate is

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estimated as $\sim 10^{-7}$ to 10^{-6} per typical galaxy per year under isotropic assumption. (6) The lifetime of the central engines should be $\sim$10–100 s, during which the energy release should be highly variable (Sari & Piran 1997; Kobayashi, Piran, & Sari 1997).

On the other hand, radio pulsars are observed to have a mean three-dimensional velocity of 200–500 km s^{-1}, with a significant population having velocities greater than 1000 km s^{-1} (Frail, Goss, & Whiteoak 1994; Cordes & Chernoff 1998). Since the average space velocity of normal stars in the Milky Way is only about 30 km s^{-1}, it is generally believed that pulsars must receive a substantial "kick" at birth (van Den Heuvel & van Paradijs 1997; Spruit & Phinney 1998; Lai, Chernoff, & Cordes 2001). Neutron star kick is surely one of the most catastrophic and violent processes in the universe. While the result of the process (i.e., large proper motions of neutron stars) has been definitely observed, it seems that we still do not detect any phenomena that are directly connected to the kick process itself. Note that supernovae are still not the specific phenomena that we are talking about, since we can never predict just from the supernova observations whether or not a high-speed neutron star has been produced. Here we suggest that the mysterious GRBs are just the interesting phenomena that we are looking for, i.e., the emergence of a GRB may indicate the birth of a high-speed neutron star.

The possible intrinsic connection between GRBs and neutron star kicks was first realized by Dar & Plaga (1999; also see Dar 1999). They assumed that a relativistic jet is responsible for the large kick velocity of pulsars. The jet then potentially has the ability to account for a GRB. Denoting the mass of the high-speed neutron star as $M_{\rm NS}$ and its kick velocity as $V_{\rm NS}$, the total energy ($E_{\rm flow}$) enclosed in the recoiling outflow can be easily calculated from momentum conservation (Dar & Plaga 1999; Dar 1999),

$$E_{\rm flow} = M_{\rm NS} V_{\rm NS} c = 8.3 \times 10^{51}\ {\rm ergs} \times \left(\frac{M_{\rm NS}}{1.4\ M_\odot}\right)\left(\frac{V_{\rm NS}}{1000\ {\rm km\ s^{-1}}}\right), \quad (1)$$

where c is the speed of light. However, usually not all of this energy can be used to power a GRB. Assuming that a portion ϵ of $E_{\rm flow}$ is deposited into electron-positron pairs and that they are beamed into a cone with a small half-opening angle of θ, then an on-axis observer will detect an intense GRB with an isotropic equivalent energy of

$$E_{\rm iso} = \frac{2\epsilon E_{\rm flow}}{1-\cos\theta} \approx 4\epsilon M_{\rm NS} V_{\rm NS} c \theta^{-2} = 3.3 \times 10^{53}\ {\rm ergs} \times \left(\frac{\epsilon}{0.1}\right)\left(\frac{\theta}{0.1}\right)^{-2}\left(\frac{M_{\rm NS}}{1.4 M_\odot}\right)\left(\frac{V_{\rm NS}}{1000\ {\rm km\ s^{-1}}}\right). \quad (2)$$

For ϵ values as high as 0.3 and θ values as low as 0.05, $E_{\rm iso}$ can reach $\sim 4.0 \times 10^{54}$ ergs, enough to account for all the GRBs localized so far. We thus see that GRBs could basically be due to the birth of high-speed neutron stars ($V_{\rm NS} \geq 1000$ km s^{-1}).

3. KICK MECHANISM

To evaluate ϵ and θ more rationally and to examine whether this mechanism can meet other observational requirements listed at the beginning of § 2, we must resort to the details of kick mechanism, which itself, however, is still a bit uncertain. According to the characteristics of the recoiling outflows, current kick models can be divided into three main categories, i.e., hydrodynamically driven kicks, neutrino-driven kicks, and electromagnetic radiation–driven kicks (Lai, Chernoff, & Cordes 2001). We discuss them one by one below.

In hydrodynamically driven kick mechanisms, asymmetric matter ejection and/or asymmetric neutrino emission due to global asymmetric perturbations of presupernova cores are involved (Janka & Müller 1994; Burrows & Hayes 1996). The timescale of the kick process has been estimated as $\tau_{\rm kick} \sim 0.1$ s (Lai, Chernoff, & Cordes 2001). However, it turns out to be very unlikely that these mechanisms are able to account for the observed pulsar velocities in excess of about 500 km s^{-1} (Janka & Müller 1994). They should be irrelevant to the high-speed neutron stars that interest us here.

In neutrino-driven kick mechanisms, asymmetric neutrino emission induced by strong magnetic fields acts as the working medium of the rocket effect. There are mainly two kinds of detailed mechanisms. In the first mechanism, since the cross section for ν_e ($\bar{\nu}_e$) absorption on neutrons (protons) depends on the local magnetic field strength, asymmetric neutrino emission can be produced if the field strengths at the two opposite poles of the neutron star are different. To generate a recoil velocity of $V_{\rm NS} \sim 300$ km s^{-1} would require that the difference in the field strengths at the two opposite stellar poles be at least 10^{16} G (Lai et al. 2001; Lai & Qian 1998). The second mechanism relies on the effect of parity violation, which indicates that the neutrino opacities and emissivities in a strongly magnetized nuclear medium depend asymmetrically on the directions of neutrino momenta with respect to the magnetic field (Lai et al. 2001; Arras & Lai 1999). The resulting kick velocity is $V_{\rm NS} \sim 50(B/10^{15}\ {\rm G})$ km s^{-1}. To generate a recoil velocity of 1000 km s^{-1}, the magnetic field would have to be $B \sim 2 \times 10^{16}$ G. Although evidence for the existence of magnetars with superstrong magnetic field approaching 10^{15} G has been revealed in soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs) (Thompson & Duncan 1995; Kouveliotou et al. 1998; Hurley et al. 1999; Ibrahim, Swank, & Parke 2003), a field strength of $B \geq 2 \times 10^{16}$ G at the neutron star surface is still unimaginably too large. The birth of high-speed neutron stars is not likely to be due to these mechanisms.

Now we come to discuss the third class of kick mechanisms—electromagnetic radiation–driven kicks. It has been shown that electromagnetic radiation from a rotating off-centered magnetic dipole imparts a kick to the neutron star (Harrison & Tademaru 1975; Lai et al. 2001). The kick comes at the expense of the spin kinetic energy. Under optimal conditions, the maximum kick velocity would be (Lai et al. 2001)

$$V_{\rm NS} \sim 1400(R/10\ {\rm km})^2(P/1\ {\rm ms})^{-2}\ {\rm km\ s^{-1}}, \quad (3)$$

where R and P are the radius and period of the neutron star, respectively. Note that the rotational kinetic energy of a neutron star with a moment of inertia of I is (Usov 1992),

$$E_{\rm spin} = \frac{1}{2} I \left(\frac{2\pi}{P}\right)^2 \approx 2 \times 10^{52}\left(\frac{I}{10^{45}\ {\rm g\ cm^2}}\right)\left(\frac{P}{1\ {\rm ms}}\right)^{-2}\ {\rm ergs}, \quad (4)$$

enough to meet the requirement of equation (1). This electromagnetic rocket effect is usually considered as a "postnatal" kick, since for typical neutron stars with $B \sim 10^{12}$ G, the kick is attained on the initial spin-down timescale of $\tau_{\rm kick} \geq 10^9$ s. However, if the pulsar is a magnetar with a superstrong magnetic field, then the lifetime of the kick can be tens of seconds, i.e. (Usov 1992; Lai et al. 2001),

$$\tau_{\rm kick} \approx 50\left(\frac{B}{3\times10^{15}{\rm G}}\right)^{-2}\left(\frac{P}{1~{\rm ms}}\right)^{2}~{\rm s}~. \tag{5}$$

Since the existence of magnetars with superstrong magnetic field approaching 10^{15} G has been creditably proved from the studies of SGRs and AXPs (Thompson & Duncan 1995; Kouveliotou et al. 1998; Hurley et al. 1999; Ibrahim et al. 2003), we believe that electromagnetic radiation–driven kick is the most viable mechanism responsible for the birth of high-speed neutron stars. We will continue our analysis on the connection between GRBs and neutron star kicks in this frame work.

4. GRBs FROM NEUTRON STAR KICKS

Particle generation and acceleration at the surface of a millisecond magnetar have been studied in great detail by Usov (1992). Although the magnetic dipole involved here is off-centered, the process should largely be similar. As demonstrated by Usov, the component of electric field along magnetic field in the magnetosphere of a millisecond magnetar is extremely high. Plenty of electron-positron pairs are created directly as the result of the vacuum discharge ($E \rightarrow e^+ + e^- + E$; Usov 1992). In addition, pair creation through one-photon ($\gamma + B \rightarrow e^+ + e^- + B$) and two-photon processes ($\gamma + \gamma \rightarrow e^+ + e^-$) may also play an important role in the process. Usov estimated that the fraction of the total spin-down energy that finally goes into electron-positron pairs, i.e., ϵ in equation (2), is a few times 0.1.

Usov assumed that these energetic particles are emitted isotropically. This may deviate from the reality. According to pulsar theories (Ruderman & Sutherland 1975; Cheng, Ho, & Ruderman 1986), particle generation and acceleration most likely occur at the polar cap or in a small region slightly above it. The emission of high-energy particles thus should mainly be along the magnetic axis. In fact, the duty cycle (i.e., pulse width divided by period and then times 360°) of radio pulsars is typically found to be $W_{\rm pulse} \sim 10^{\rm o}$, with a few exceptions where $W_{\rm pulse}$ can be as small as $\sim 3°$ or as large as tens of degrees (Manchester & Taylor 1977). It is reasonable that the half-opening angle of the primary electron-positron outflow will be less than $W_{\rm pulse}/2$. So, the θ parameter in equation (2) can typically be evaluated as $\theta \sim 0.1$ rad, with the possibility that it can be as small as $\theta \sim 0.03$ rad in some cases.

From the above analysis, we are convinced that GRBs really could be due to the kicks of high-speed neutron stars. This model naturally meets the direct observational requirements listed in § 2: (1) The deposited energy is enough for GRBs. The isotropic equivalent energy can easily exceed 5×10^{54} ergs. (2) The collimation is safely guaranteed, with a typical beaming angle $\theta \sim 0.1$. (3) The ultrarelativistic motion (with Lorentz factor $\gamma \geq 100$–1000) is reasonably expected, since the original outflows here are mainly composed of electrons and positrons. (4) The model naturally explains the observed connection between GRBs and supernovae (for details, see Dado et al. 2002b, 2003) and the association of GRBs with star-forming regions. (5) In this model, the durations of GRBs are obviously determined by the timescale of the kick process, which has been given in equation (5). It is in good agreement with observations. (6) The model also meets the requirement of GRB event rate. Let us have a look at this problem in some detail. The supernova rate in our Galaxy is $\sim$1/50–1/30 yr^{-1} (Tammann, Löffler & Schröder 1994; van Den Bergh & McClure 1994). Then the birthrate of neutron stars in a typical galaxy can be estimated as $\sim 10^{-2}$ yr^{-1}. The percentage of high-speed neutron stars is still a bit uncertain but should be some value between 1% and 10% (Frail et al. 1994; Cordes & Chernoff 1998). So, the birthrate of high-speed neutron stars is $\sim 10^{-4}$ to 10^{-3} galaxy^{-1} yr^{-1}. However, GRB emission from these objects is typically beamed into a small cone with a half-opening angle of $\theta \sim 0.1$. After compensating for the beaming effect, the predicted detectable GRB event rate will be $\sim 10^{-7}$ to 10^{-6} galaxy^{-1} yr^{-1}, which is consistent with observations.

The model also has the potential advantage of satisfying many other requirements inferred indirectly from GRB observations. For example, the fast variability in GRB light curves indicates that internal shocks are preferable during the main GRB phase (Kobayashi, Piran, & Sari 1997). In our model, the possibility of generating internal shocks is greatly increased thanks to the recently discovered apparent alignment of the spin axes and proper motion directions of the Crab and Vela pulsars (Caraveo & Mignani 1999; Pavlov et al. 2000). This alignment indicates that the timescale of the kick will generally be much larger than the spin period of the neutron star and that the velocity of the kicked material could make a nonzero angle Θ to the spin axis (Lai et al. 2001). In other words, the GRB might come from a precessing jet (Fargion & Salis 1995; Hartmann & Woosley 1995; Blackman, Yi, & Field 1996; MacFadyen & Woosley 1999; Fargion 1999). In this case, equations (1) and (2) will become

$$E_{\rm flow} = \frac{M_{\rm NS} V_{\rm NS} c}{\cos\Theta}~, \tag{6}$$

$$E_{\rm iso} \geq \frac{2\epsilon M_{\rm NS} V_{\rm NS} c}{\theta \sin 2\Theta} = \frac{1.7\times10^{52}~{\rm ergs}}{\sin 2\Theta}\frac{\epsilon}{0.1} \times\left(\frac{\theta}{0.1}\right)^{-1}\left(\frac{M_{\rm NS}}{1.4~M_\odot}\right)\left(\frac{V_{\rm NS}}{1000~{\rm km~s^{-1}}}\right)~, \tag{7}$$

for $\theta \ll \Theta$ and $\theta \ll 1$. Equation (7) means that the GRB appears less powerful now, but the possibility that it can be detected increases by a factor of $\sim 4 \sin\Theta/\theta$. The precession of the jet may help to explain the rapid variability observed in GRB light curves (Roland, Frossati, & Teyssier 1994; Portegies-Zwart, Lee, & Lee 1999). We also notice that the space velocities of the Vela and Crab pulsars are not too large, i.e., $\sim$70–141 and $\sim$171 km s^{-1}, respectively (Lai et al. 2001). For high-speed neutron stars, we believe that the Θ values will be very small, so that equation (2) is still approximately applicable.

Frail et al. suggested that the gamma-ray energy release in GRBs, corrected for geometry, is narrowly clustered around 5×10^{50} ergs (Frail et al. 2001). It is interesting that our model strongly supports their conclusion. From equation (1) we see that the total energy enclosed in the recoiling outflow is $E_{\rm flow} \sim 8 \times 10^{51}$ ergs, the energy in the electron-positron plasma is then $\epsilon E_{\rm flow} \sim 8 \times 10^{50}$ ergs. The relatively wide variation in fluence and luminosity of GRBs observed so far should mainly be due to a distribution of the opening angle θ appearing in equation (2).

It has long been recognized that GRB durations are distributed bimodally, with short bursts clustered around $\sim$0.2 s and long events clustered around $\sim$20 s (Mazets et al. 1981; Mao, Narayan, & Piran 1994). Currently, afterglows have been observed only from long GRBs, so that the distances and the nature of short GRBs are completely uncertain. It is very interesting that our model also provides a natural explanation for the existence of these short bursts, since the progenitors here are millisecond magnetars. The advantage of millisecond magnetars to explain the bimodal duration distribution of GRBs has been discussed by Usov (1992) and Yi & Blackman (1998). The key point is that there exists a critical rotating period ($P_{\rm cr}$) for pulsars. The critical period $P_{\rm cr}$ depends on neutron star mass and is $\sim$0.5–1.6 ms (Friedman 1983; Usov 1992). If a pulsar rotates with a period smaller than $P_{\rm cr}$, instability arises inside the compact star so that gravitational radiation plays the major role in braking the fast rotator. In this case, the spin-down timescale becomes (Usov 1992)

$$\tau_{\rm GW} \approx 0.12\left(\frac{\varepsilon}{0.1}\right)^{-2}\left(\frac{P}{0.5\ {\rm ms}}\right)^{4}\ {\rm s}, \quad \text{with } P < P_{\rm cr}, \qquad (8)$$

where ε is the equatorial ellipticity of the neutron star and is typically a few times 0.1. Abundant high-energy particles emitted during this quick deceleration phase can generate the observed short GRBs (Usov 1992; Yi & Blackman 1998). A reasonable inference of this model is that short GRBs might also be highly collimated. The testing of such collimation will be an interesting goal in future observations of short GRBs. Furthermore, the observed number of short GRBs relative to that of long GRBs might give us some hints on the distribution of the initial periods of magnetars at birth.

5. CONCLUSION AND DISCUSSION

The connection between GRBs and neutron star kicks is a natural deduction from momentum conservation (Dar & Plaga 1999; Dar 1999). Here we suggest that the neutron star in this mechanism will be a high-speed one, with velocity larger than $\sim$1000 km s^{-1}. We have shown that the model can naturally satisfy many of the observational constraints on the central engine of GRBs. For example, it well explains the energetics, the collimation, the event rate, the ultrarelativistic motion, the light-curve variability in gamma rays, the bimodal distribution of durations, the narrowly clustered intrinsic energy, and the association of GRBs with supernovae and star-forming regions. We also discuss the implications of this model on the neutron star kick mechanism and suggest that the high kick speed is most likely acquired as a result of the electromagnetic rocket effect of a millisecond magnetar with an off-centered magnetic dipole.

In all our discussion in the previous sections, we have assumed that a single recoiling outflow is responsible for the kick of the pulsar. However, Dar et al. (Dar & Plaga 1999; Dar 1999) have pointed out that in realistic case two antiparallel jets might be ejected by the neutron star. Then it is the momentum imbalance in these two jets that is responsible for the large kick velocity. In this case, the energy in equation (1) is only a lower limit of the dominant jet. An interesting consequence of this picture is that in some cases it might be the weaker jet, not the dominant one, that is pointing toward us. Since the energy is much less now, it is very likely that we would observe a failed gamma-ray burst (FGRB), i.e., a relativistic outflow with the Lorentz factor $1 \ll \gamma \ll 100$–1000 (Huang, Dai, & Lu 2002). Huang et al. (2002) have suggested that such FGRBs might give birth to the so-called X-ray flashes, a kind of GRB-like X-ray transients that were identified very recently (Strohmayer et al. 1998; Frontera et al. 2000; Kippen et al. 2001; Barraud et al. 2003). Totani (2003) further pointed out clearly that FGRBs might usually be associated with supernovae.

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