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Pulsar kicks and γ-ray burst

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ABSTRACT

Aims. We use the supernova-GRB (γ-ray burst) association and assume that the GRB asymmetric explosions produce pulsars in order to test the consistency of distributions of modeled and observed pulsar-kick velocities.
Methods. The deduced distribution of kick velocity from the model of GRB and the observed kick distribution of radio pulsars are checked by a K-S test.
Results. These two distributions are found to come from the same parent population.
Conclusions. This result may indicate that GRBs could really be related to supernova and that the asymmetry of GRB associated with supernova would cause the pulsar kick.

Key words. stars: pulsars: general – gamma rays: bursts – stars: neutron – dense matter

1. Introduction

The difficulty of reproducing two kinds of astronomical bursts are challenging today's astrophysicists to find realistic explosive mechanisms. On one hand, γ-ray bursts (GRBs) are puzzling phenomena, the center engine of which is still an outstanding problem, although the related fireball models are effective in explaining accumulative observational data. The launch of Swift is stimulating study in this area (see Zhang 2007, for a recent review). On the other hand, failure to simulate supernovae (SNe) successfully in the neutrino-driven explosion model has troubled astrophysicists for a long time, and the call for alternative mechanisms has grown stronger and stronger (Mezzacappa 2005; Buras et al. 2003).

The discovery of 4 clear associations (and many SN bumps in the late optical afterglow light curves) between long, soft GRBs and Type II/Ibc SNe (see, e.g., the review by Woosley & Bloom 2006) results in finding common explosive processes for SNe and GRBs to form rapidly spinning black holes (Woosley 1993), neutron stars (Kluźniak & Ruderman 1998), or even quark stars (Dai & Lu 1998). It is worth noting that GRB as a signature of phase transition to quark-gluon plasma (Xu et al. 1999; Wang et al. 2000; Yasutake et al. 2005; Paczyński & Haensel 2005; Drago et al. 2007; Haensel & Zdunik 2007) has also wide implications for the study of elementary interactions between quarks. It has suggested that the *bare* quark surfaces could be essential to successful explosions of both GRBs and SNe (Xu 2005; Paczyński & Haensel 2005; Chen & Xu 2006) because of chromatic confinement (the photon luminosity of a quark surface is then not limited by the Eddington limit). For simplicity, the one-dimensional (i.e., spherically symmetric) calculation of Chen & Xu (2006) shows that the lepton-dominated fireball supported by a bare quark surface does play a significant role in the explosion dynamics under such a photon-driven scenario. However, what if the expanding of a fireball outside the quark surface is not spherically symmetric? That asymmetry may naturally result in kicks on quark stars. But how can we test this idea? These issues are focus here.

Quark stars could reproduce the observational features of pulsar-like stars well (Xu 2006). Radio pulsars have long been recognized of having high space velocities (e.g. Gunn & Ostriker 1970; Lorimer et al. 1997; Lyne et al. 1982; Cordes & Cherno 1998). Lyne & Lorimer (1994) observed a high mean velocity of pulsars: $\upsilon \approx 450 \pm 90$ km s^{-1}. From a comparison with a Monte Carlo simulation, Hansen & Phinney (1997) found that the mean birth speed of a pulsar is ~250–300 km s^{-1}. Applying the recent electron density model to determining pulsar distances, Hobbs et al. (2005) gave mean two-dimensional (2D) speeds of 246 ± 22 km s^{-1} and 54 ± 6 km s^{-1} for the normal and recycled pulsars, respectively.

However, the origin of these kicks is still a matter of debate. In 1994, Lyne & Lorimer suggested that any small asymmetry during the explosion can result in a substantial "kick" to the center star. From the observation of binary pulsar, Lai et al. (1995; see also Lai 1996) also proposed that the pulsar acquired its velocity from an asymmetric SN collapse. In 1996, Burrows & Hayes argued that an anisotropic stellar collapse could be responsible for pulsar kicks. Then, Cen (1998) proposed that an SN produces a GRB and a strong magnetized, rapidly rotating NS emitting radio pulse; and for the first time, the author related the kicks of pulsars to GRBs. Dar & Plaga (1999) proposed that the natal kick may arise from the emission of a relativistic jet from its compact center star. Lai et al. (2001) pointed out three kick mechanisms: an electromagnetic rocket mechanism (Harrison & Tademaru 1975), hydrodynamically driven and neutrino-magnetic field driven kicks. Considering these three kick mechanisms, Huang et al. (2003) found that the model of Dar & Plaga (1999) agrees well with the observations of GRBs. After investigating the spectra and the light curve of SN2006aj associated with an X-ray flash (GRB060218), Mazzali et al. (2006) found that the progenitor of the burst is a star, whose

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initial mass was only $\sim 20\ M_\odot$, expected to form only a residual neutron star rather than a black hole when its core collapses.

In this work, we present a statistical model where the kick velocity of a pulsar arises from the asymmetric explosion of a mono-jet GRB. Although the mechanism for the formation of one-side jet is based neither on observational evidence nor on firm theoretical evidence, the key point here, as mentioned by Cen (1998), is to couple a significant fraction of the total gravitational collapse energy of the core to a very small amount of baryonic matter. We suggest that SNe (to form pulsars) and GRBs are generally associated and try to know if the observed pulsar's kicks and the modeled one from GRB luminosity are statistically consistent. After comparing the distribution of an observed pulsar's kick velocities with that from GRB energies, we find that these two distributions may come from the same parent population. In Sect. 2, we give the samples and equations for statistics. The statistical results are presented in Sect. 3, and conclusions and discussions are offered in Sect. 4.

GRBs have been classified into long-soft and short-hard categories. The former is currently supposed to be associated with the death of massive stars, while the latter is suggested as being related to the mergers of compact stars in elliptical/early-type galaxies (Gehrels et al. 2005). We focus only on long-soft GRBs in this paper.

2. Samples and equations

From the ATNF pulsar catalogue[1], 121 isolated pulsars with known kick velocities are obtained, where the archived velocity is the transverse velocity, i.e. the projection of three-dimensional (3D) kick velocity on the celestial sphere. The GRB sample applied in this paper is currently the largest one with known redshifts[2], z. It includes 98 GRBs, out of which are 66 with known fluences detected by BATSE (at 110–320 keV) or HETE II (30–400 keV) or Swift (15–150 keV).

If a neutron star forms after the asymmetric explosion of a GRB, other debris escape from one side with almost the speed of sight, c, due to the huge energy released. According to the conservation of momentum, the neutron star's momentum should be $P_\mathrm{m} = E_\gamma/c$, with E_γ the total energy of GRBs. The kick velocity is then $\upsilon = P_\mathrm{m}/M_\mathrm{NS}$. Here we adopt the mass of neutron star, M_NS, as the typical one of 1.4 $M_\odot$, given by Stairs (2004) from the high-precision pulsar timing observations.

The collimation-corrected total energy of GRBs from a conical jet reads (Dado et al. 2006)

$$E_\gamma = \frac{1}{2}(1-\cos\theta)E_\mathrm{iso}, \tag{1}$$

where θ is the opening angle of jet, and E_iso is the isotropic burst energy that is derived from observed fluence and distance, or some models do it by assuming an isotropic burst. Ghirlanda et al. (2004) suggested that the maximum opening angle is about $\theta_\mathrm{max} = 24^\mathrm{o}$. In this paper, the opening angle for each GRB is generated randomly within $\theta < \theta_\mathrm{max}$.

The method for calculating E_iso, which applies to 66 GRBs with observed fluence S and redshift z, is based on the relation

$$E_\mathrm{iso} = \frac{4\pi\kappa D_\mathrm{L}^2}{1+z}S, \tag{2}$$

where D_L is the luminosity distance of GRB, which, for the sake of simplicity, is calculated by adopting $\Omega_\mathrm{M} = 0.3$, $\Omega_\Lambda = 0.7$, and

[1] http://www.atnf.csiro.au/research/pulsar/psrcat/

[2] http://www.mpe.mpg.de/~jcg/

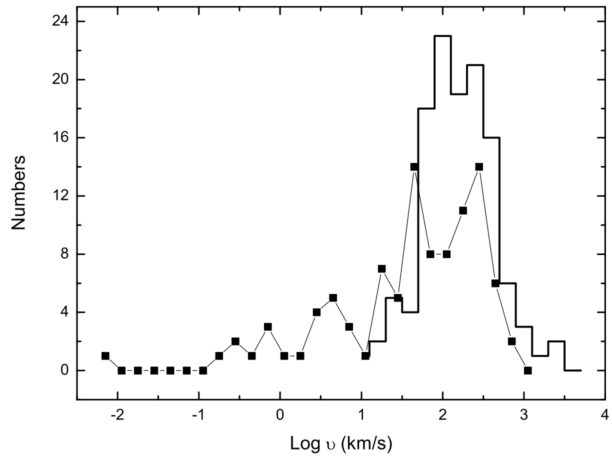

Fig. 1. The distribution of the pulsar's kick velocity and that derived from GRB model. The solid step line is the observed kick distribution for the 121 pulsars in ATNF. The line with symbols is the modeled kick distribution derived from the observed fluences and redshifts of GRB.

$H_0 = 71$ km s^{-1} Mpc^{-1}. The factor κ is applied to convert the observed fluence at the observational energy band of an instrument (from E_1 to E_2, in unit of keV) to that at a standard band in rest frame of GRB, $(1-10^4)/(1+z)$ keV (Bloom et al. 2001), which reads

$$\kappa = \frac{\int_{1/(1+z)}^{10^4/(1+z)} EN(E)\mathrm{d}E}{\int_{E_1}^{E_2} EN(E)\mathrm{d}E}, \tag{3}$$

where E is photon energy, $N(E)$ the band function defined by Band et al. (1993) as

$$N(E) \propto \begin{cases} E^\alpha \mathrm{e}^{-E/E_0} & E \leq (\alpha-\beta)E_0 \\ [(\alpha-\beta)E_0]^{\alpha-\beta} E^\beta \mathrm{e}^{\alpha-\beta} & E > (\alpha-\beta)E_0 \end{cases}, \tag{4}$$

where α and β are the spectral indices of GRBs. In our calculation, the statistical mean spectral indices $\alpha \simeq -1$, $\beta \simeq -2.2$ are substituted into the $N(E)$ formula (Preece et al. 2000). The peak photon energy, E_0, is adopted to be $E_0 \simeq 200$ keV.

Substituting E_iso obtained with Eqs. (2)–(4) into Eq. (1) to calculate E_γ, one can figure out the modeled kick velocity for each GRB. However, the velocity is 3D (υ_3D). To compare its distribution with that of the archived velocity of pulsars, which is the 2D velocity on the celestial sphere, one needs to use "$\upsilon_\mathrm{2D} = \upsilon_\mathrm{3D} \cdot \sin\phi$" to do projection, where ϕ is the angle between line of sight and $\boldsymbol{\upsilon}_\mathrm{3D}$. In our calculation, ϕ is obtained by generating a normalized random number for $\sin\phi$ for each GRB, but not by generating a random value for ϕ directly. That is because the direction of kick velocity should be isotropic in space, and the probability from ϕ to $\phi + \mathrm{d}\phi$ is proportional to $\sin\phi$. (Note: it could be easily obtained by considering the solid angle between ϕ and $\phi + \mathrm{d}\phi$.)

3. Results

With the modeled velocities, υ_2D, obtained with above equations, the distribution is plotted in Fig. 1. The histogram of the ATNF-archived kick velocity of pulsars is also shown in the figure. The null hypothesis for two groups, i.e. the distributions of the model above and observed velocities, is tested with a Kolmogorov-Smirnov (K-S) test, with P_KS the maximum distance between the cumulative probability functions and p the significant level. The

Table 1. The K-S test results for the kick velocity of pulsar sub-classes and GRB sample.

Sample	$MSP14$	$NP107$	$Young44$	$old73$
$GRB66$	0.30 (0.52)	0.33 (0.25)	0.18 (0.90)	0.17 (0.92)

maximum distance between their cumulative probability functions is $P_{\rm KS} = 0.36$ on the significant level $p = 0.15$. This indicates that one can not reject the null hypothesis, viz. a common origin of the two samples, at the 5% significance level.

4. Conclusions and discussions

Based on the assumption that NSs are produced in asymmetric explosions of GRBs associated with SNe and the conservation law of momentum, we calculated the kick velocity of NSs from the model of GRBs. Comparing the distribution of modeled kick velocity with that of the observed kick velocity of pulsars, it is found that the two distributions come from the same parent population. Therefore, we conclude that the kick velocity of pulsars may come from the asymmetric explosion of GRBs. Our work could be regarded as an observational test of the idea proposed by Cen (1998) who suggested a unified scenario that explains both pulsar kicks and cosmic GRBs.

To test the effect of the rotation period P, we classified the pulsar sample into millisecond and normal pulsars and compared the distributions with modeled kick velocity by a K-S test. Designated $P = 20$ ms as the critical period, there are 14 millisecond pulsars (hereafter "$MSP14$") and 107 normal pulsars ("$NP107$"). The distributions of these two sub-samples are compared with the GRB sample, i.e. "$GRB66$" (the modeled kick velocity derived from the 66 GRBs with observed fluences and redshifts), via a K-S test. The results are listed in Table 1. In the bracket is the significant level p for the corresponding maximum distance $P_{\rm KS}$ between the cumulative probability functions.

The effect of the characteristic age τ is also tested. Assigning the characteristic age $\tau_0 = 4 \times 10^6$ yrs, we find 44 pulsars with $\tau < \tau_0$ (sub-sample "$Young44$") and 73 with $\tau > \tau_0$ (sub-sample "$old73$"). Note that there are 4 pulsars without detected ages. The results of K-S test are also presented in Table 1.

From Table 1, all the values of significant level for $P_{\rm KS}$ are higher than 0.05 to indicate that two sub-samples in any pair come from the same parent population. It implies that the consistency of modeled and observed kick velocity distributions may be intrinsic and does not change with pulsar's periods or ages.

In summary, a primary statistical test of the consistency of the kick velocity distributions from the model of SN-related GRB and from the observations of pulsars is done via a K-S test. Advanced research to check the idea that asymmetric fireballs result in kicks is needed as more related observational data will be possible in the future. Statistically, we find that the distribution of observed pulsar's kicks may be consistent with what is deduced from the model of GRBs under the assumption that pulsar kicks arise from the one-sided explosion of SN-related GRB. Comprehensively theoretical understanding on this statistics is still not certain and is very necessary.

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