Pulsar’s kicks and γ-ray bursts

X. H. Cui,1 H. G. Wang,2 R. X. Xu,3 and G. J. Qiao1

1 Astronomy Department, School of Physics, Peking University, Beijing 100871, China
e-mail: (xhcui,rxxu,gjqi)@pku.edu.cn
2 Center for Astrophysics, Guangzhou University, Guangzhou 510400, China
e-mail: cosmic008@263.net

Received ; accepted

ABSTRACT

Aims. The consistence of the distributions of pulsar’s kick velocities from the model of GRB and from the pulsar observations is tested based on the supernova-GRB (γ-ray burst) association and under the assumption that the GRB asymmetric explosions produce pulsars.

Methods. The deduced distribution of kick velocity from the model of GRB and the observed kick distribution of radio pulsars are checked by K-S test.

Results. These two distributions are found to come from a same parent population.

Conclusions. This result may indicate that GRBs could be really related to supernova, and that the asymmetry of GRB associated with supernova would cause the kick of pulsars.

Key words. 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 have been well-developed due to accumulation of more and more observational data. The launch of Swift is stimulating the study in this area (see Zhang 2007 for a recent review). On the other hand, the failure to simulate supernovae (SNe) successfully in the neutrino-driven explosion model troubles astrophysicists over long time, and the call for alternative mechanisms grew 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 spinning rapidly 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, Pagliara & Parenti 2007; Haensel & Zdunik 2007) also has great implications in the study of elementary interactions between quarks. It was addressed 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 the chromatic confinement (the photon luminosity of a quark surface is not then limited by the Eddington limit). For simplicity, 1-dimensional (i.e., spherically symmetric) calculation of Chen & Xu (2006) shows that the lepton-dominated fireball supported by a bare quark surface do play a significant role in the explosion dynamics under such a photon-driven scenario. However, what if the expanding of a fireball outside quark surface is not spherically symmetric? That asymmetry may naturally result in kicks of quark stars. But how to test this idea? These issues will be focused here.

Quark stars could well reproduce the observational features of pulsar-like stars (Xu 2006). Radio pulsars have long been recognized to have great space velocities (e.g. Gunn & Ostriker 1970; Lorimer, Bailes, & Harrison 1997; Lyne, Anderson & Salter 1982; Cordes & Chernoff 1998). Lyne & Lorimer (1994) have observed a large mean velocity of pulsars $v \approx 450 \pm 90$ km s$^{-1}$. From a comparison with Monte Carlo simulation, Hansen & Phinney (1997) found that the mean birth speed of a pulsar is $\sim 250 - 300$ km s$^{-1}$. Applying the recent electron density model to determine pulsar distances, Hobbs et al. (2005) gave mean two-dimensional (2D) speeds of $246 \pm 22$ km s$^{-1}$ and $54 \pm 6$ 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 generally that any small asymmetry during the explosion can result in a substantial “kick” to the center star. From the observation of binary pulsar, Lai, Bildsten & Kaspi (1995; see also Lai 1996) proposed also 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. Cen (1998) proposed that a 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 of its center compact star. Lai, Chernoff & Cordes (2001) pointed out three kick
mechanisms: 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 initial mass was only \( \sim 20M_\odot \), 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 distribution of observed pulsar’s kicks and the modelled one from GRB luminosity are statistically consistent. After comparing the distribution of observed pulsar’s kick velocities with that from GRB energies, we find that these two distributions may come from same parent population. In §2, we give the samples and equations for statistics. The statistical results are presented in §3. Conclusions and discussions are made in §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 to be 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 velocity 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 redshift\(^2\)\( z \). It includes 98 GRBs, out of which 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 \( P_m = E_x / c \), with \( E_x \) the total energy of GRBs. The kick velocity is then \( v = P_m / M_{\text{NS}} \). Here we adopt the mass of neutron star, \( M_{\text{NS}} \), 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),

\[
E_\gamma = \frac{1}{2} (1 - \cos \theta) E_{\text{iso}},
\]

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

The method to calculate \( E_{\text{iso}} \), which applies to 66 GRBs with observed fluence \( S \) and redshift \( z \), is based on the following relation,

\[
E_{\text{iso}} = \frac{4\pi \kappa D_L^2}{1 + z} S,
\]

where \( D_L \) is the luminosity distance of GRB, which, for the sake of simplicity, is calculated by adopting \( \Omega_M = 0.3, \Omega_\Lambda = 0.7, \) and \( H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1} \). The factor \( \kappa \) is applied to convert the observed fluence at 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, \((1 - 10^4)/(1 + z) \text{ keV} \) (Bloom et al. 2001), which reads,

\[
\kappa = \frac{\int_{E_1}^{E_2} EN(E) dE}{\int_{E_1}^{E_2} EN(E) dE},
\]

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

\[
N(E) \propto \begin{cases} E^{\alpha} e^{-E/E_0} & \text{if } E \leq (\alpha - \beta)E_0 \\ E^{\beta} e^{-E/E_0} & \text{if } E > (\alpha - \beta)E_0 \\ \end{cases}
\]

where \( \alpha \) and \( \beta \) are spectral indices of GRBs. In our calculation, the statistic mean spectral indices \( \alpha \sim -1, \beta \sim -2.2 \) are substituted into \( N(E) \) formula (Preece et al. 2000). The peak photon energy, \( E_0 \), is adopted to be \( E_0 \approx 200 \text{ keV} \).

Substituting \( E_{\text{iso}} \) obtained with Eqs.(2-4) into Eq.(1) to calculate \( E_x \), one can figure out the modelled kick velocity for each GRB. However, the velocity is three dimensional (\( v_{3\text{D}} \)). In order to compare its distribution with that of the archived velocity of pulsars, which is two dimensional velocity on celestial sphere, one needs to use \( "v_{2\text{D}} = v_{3\text{D}} \cdot \sin \phi" \) to do projection, where \( \phi \) is the angle between line of sight and \( v_{3\text{D}} \). In our calculation \( \phi \) is obtained by generating a normalized random number for \( \sin \phi \) for each GRB, but not by generating a random value for \( \phi \) directly. That is because the direction of kick velocity should be isotropic in space, the probability from \( \phi \) to \( \phi + d\phi \) is proportional to \( \sin \phi \) (note: it could be easily obtained by considering the solid angle between \( \phi \) and \( \phi + d\phi \)).

3. Results

With the modelled velocities, \( v_{2\text{D}} \), obtained with above equations, the distribution is plotted in Fig.1, as shown by line with symbols. The histogram of ATNF-archived kick velocity of pulsars (solid line) 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 Kolmogorov-Smirnov (K-S) test. The maximum distance between their cumulative probability functions is \( P_{\text{KS}} = 0.36 \) on the significant level \( p = 0.15 \). This indicates that the samples of observed and modelled kick velocity could come from the same parent population.

\( \text{http://www.atnf.csiro.au/research/pulsar/psrcat/} \)

\( \text{http://www.mpe.mpg.de/~jcg/} \)
4. Conclusions and discussions

Based on the assumption that NSs are produced in asymmetric explosion of GRBs associated with SNe and the conservation law of momentum, we calculate the kick velocity of NSs from the model of GRBs. Comparing the distribution of modelled kick velocity with that of observed kick velocity of pulsars, it is found that 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 this work could be regarded as an observational test to the idea proposed by Cen (1998) who suggested a unified scenario that explains both pulsar kicks and cosmic GRBs. In order to test the effect of the rotation period $P$, we classified the pulsar sample into millisecond and normal pulsars, and compare the distributions with modelled kick velocity by 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 modelled kick velocity derived from the 66 GRBs with observed fluences and redshifts), via K-S test. The results are listed in Table 1. In the bracket is the significant level $p$ for the corresponding maximum distance $P_{KS}$ between the cumulative probability functions.

The effect of the characteristic age $\tau$ 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 $P_{KS}$ are larger than 0.05 to indicate that two sub-samples in any pair come from the same parent population. It implies that the consistency of modelled and observed kick velocity distributions may be intrinsic and does not change with pulsar’s periods or ages.

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

Acknowledgements. The authors thank helpful discussion with the members in the pulsar group of Peking University. The helpful comments and suggestions from an anonymous referee are sincerely acknowledged. This work is supported by NSFC (10573002, 10778611) and by the Key Grant Project of Chinese Ministry of Education (205001).

References

| Sample | MSP14 | NP107 | Young44 | Old73 |
|--------|-------|-------|---------|-------|
| GRB66  | 0.30 (0.52) | 0.33 (0.25) | 0.18 (0.90) | 0.17 (0.92) |

Fig. 1. The distribution of 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 modelled kick distribution derived from the observed fluences and redshifts of GRB.
Preece, R. D., Briggs, M. S., Mallozzi, R. S., Pendleton, G. N., Paciesas, W. S., & Band, D. L. 2000, ApJS, 126, 19
Stairs, I. H. 2004, Science, 304, 547
Wang, X. Y., Dai, Z. G., Lu T. et al. 2000, A&A, 357, 543
Woosley, S. E. 1993, ApJ, 405, 273
Woosley, S. E., Bloom, J.S. 2006, ARA&A, 44, 507
Yasutake, N., Hashimoto, M., Eriguchi, Y. 2005, Prog. Theor. Phys. 113, 953
Xu, R. X. 2005, MNRAS, 356, 359
Xu, R. X. 2006, ChJA&A, Proceedings of The 2005 Lake Hanas International Pulsar Symposium, in press (astro-ph/0512519)
Xu, R. X., Dai, Z. G., Hong, B. H., Qiao, G. J. 1999, astro-ph/9908262
Zhang, B. 2007, ChJA&A, in press (astro-ph/0701520)