Neutron star spin–kick velocity correlation effect on binary neutron star coalescence rates and spin–orbit misalignment of the components

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ABSTRACT
We study the effect of the neutron star spin–kick velocity alignment observed in young radio pulsars on the coalescence rate of binary neutron stars. Two scenarios are considered for neutron star formation: when the kick is always present, and when it is small or absent if a neutron star is formed in a binary system as a result of electron-capture degenerate core collapse. The effect is shown to be especially strong for large kick amplitudes and tight alignments, reducing the expected galactic rate of binary neutron star coalescence compared to calculations with randomly directed kicks. The spin–kick correlation also leads to a much narrower neutron star spin–orbit misalignment.

Key words: gravitational waves – binaries: close – stars: neutron.

1 INTRODUCTION
In the wider astrophysical community, there is increasing interest in coalescing binary compact stars as primary sources of gravitational waves for ground-based gravitational wave observatories. Double neutron stars (DNSs), observed as binary pulsars, remain the most reliable objects for gravitational wave searches. On-going LIGO science runs (Abbott et al. 2007) have already set first experimental upper limits on their galactic rates of a few per year. Astrophysical estimates of the DNS coalescence rate, which are based on binary pulsar statistics or can be obtained from population synthesis simulations, are model-dependent and vary by more than an order of magnitude around the value of $10^{-5}$ per year (see recent reviews by Postnov & Yungelson 2006; Kalogera et al. 2007 and references therein).

The kick velocity imparted to a newborn NS is an important phenomenological parameter of the core-collapse supernova (SN) and represents one of the major uncertainties in the theory of binary star evolution. The origin of the kicks remains unclear and a number of physical models have been suggested (see, for example, Lai 2004 and references therein). For post-SN evolution of a binary, both the amplitude of the kick and its space direction are important. The distribution of the kick amplitudes is usually obtained from the analysis of radio pulsar proper motions (Hobbs et al. 2005). The direction of kicks (for example, with respect to the spin axis of the NS) is more difficult to infer from observations. Recently, several observational clues have appeared, indicating possible NS spin–kick alignment. A noticeable spin–kick alignment has been inferred from polarization measurements of the radio emission of pulsars (Johnston et al. 2005, 2007; Rankin 2007), as well as from X-ray observations of pulsar wind nebulae around young pulsars (Helfand, Gotthelf & Halpern 2001; Kargaltsev, Pavlov & Garmire 2006). The implications of these findings for the formation of double pulsars have been discussed by Wang, Lai & Han (2006), Wang, Lai & Han (2007) studied the possibility and conditions for such an alignment in the model of the kick origin by multiple random kicks during NS formation (proposed by Spruit & Phinney 1998). The implication of NS kick–spin correlation to the plausible birth–kick scenarios has also been discussed by Ng & Romani (2007).

Here we explore the effect of NS spin–kick correlation on the formation and galactic coalescence rate of DNSs, which are primary targets for modern gravitational wave detectors. We show that the tighter the alignment, the smaller the DNS merging rate with respect to models with random kick orientation. The effect is especially important for large kick amplitudes ($\sim$400 km s$^{-1}$). We calculate the spin–orbit misalignment of the components of DNSs, which can be important for gravitational wave data analysis. We have also considered a scenario in which no (or insignificant) kick accompanies the formation of a NS in binary systems from the main-sequence progenitors in a restricted mass range ($\sim$8–11 M$_{\odot}$) as a result of the electron-capture collapse of the O–Ne–Ng degenerate stellar core as proposed by Podsiadlowski et al. (2004) and further elaborated by van den Heuvel (2004, 2007). This hypothesis is phenomenologically based on the existence of long-period Be X-ray binaries with low eccentricities (Pfahl et al. 2002). It is consistent with the evolutionary analysis of DNS formation (van den Heuvel 2007) and has been used in some population synthesis studies of DNSs (see, for example, Dewi, Podsiadlowski & Pols 2005; Dewi, Podsiadlowski & Sena 2006).

2 EFFECT ON THE BINARY NEUTRON STAR COALESCENCE RATES
The effect of NS kick velocity on merging rates of compact binaries has been studied previously using population synthesis simulations

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The distribution of orbital eccentricities before the second collapse in binaries producing DNSs for two kick models: kick type A, all NSs in binaries receive a kick; kick type B, the NS kick is zero in those binaries where a NS is produced from main-sequence progenitors with masses 8–11 $M_\odot$.

Consider the standard evolutionary scenario leading to the formation of a binary NS from a massive binary system (Bhattacharya & van den Heuvel 1991), which is also discussed in the review by Postnov & Yungelson (2006), focusing on the effect of the NS kick velocity. We assume that the kick velocity vector is confined within a cone that is coaxial with the progenitor’s rotation axis and characterized by angle $\theta < \pi/2$. We only consider central kicks, thus ignoring theoretically feasible off-centre kicks simultaneously affecting the NS spin (Spruit & Phinney 1998; Postnov & Prokhorov 1998; Wang et al. 2007). The value of the kick velocity is assumed to obey the Maxellian distribution $f(v) \sim v^3 \exp \{-v/v_0^2\}$, as suggested by pulsar proper motion measurements (Hobbs et al. 2005). In our analysis, we varied the velocity $v_0$ from 0 to 400 km s$^{-1}$.

The rotational axes of both components are assumed to be aligned with the orbital angular momentum before the primary collapses to form the first NS. The SN explosion is treated in a standard way as an instantaneous loss of mass of the exploding star. The effect of the kick on the post-explosion binary orbital parameters is treated using the energy-momentum conservation in the two point-mass body problem (see the description in, for example, Hills 1983; Kalogera 2000; Grishchuk et al. 2001). The first SN explosion most likely occurs when the binary orbit is circular (unless the initial binary is very wide so that tidal circularization is ineffective), while the second explosion can occur before the orbit has been tidally circularized. Possible mass transfer phases before the second collapse (such as the common envelope stage and stable mass transfer on to a NS) are assumed to effectively circularize the orbit. In the absence of mass transfer, the tidal evolution of the orbit eccentricity is treated according to Zahn (1977). In our modelling, by the time of the second collapse, the fraction of eccentric binaries that later form DNSs attains ~10 per cent depending on the kick velocity value and direction, as illustrated in Fig. 1. It is higher for isotropic kicks and increases with their absolute values. To treat the explosion in an eccentric binary, we choose the position of the star in the orbit randomly distributed according to Kepler’s second law.

We use the population synthesis method to calculate the expected DNS coalescence rate (see Lipunov et al. 1997; Postnov & Yungelson 2006 and references therein). The standard assumptions about binary evolution have been made: the Salpeter mass function for the mass of the primary, $dN/dM_1 \sim M_1^{-2.35}$; a flat initial mass ratio $\eta = M_2/M_1 < 1$ distribution $d\eta/d\log \eta = \text{const}$; initial semimajor axis distribution in the Oepik form $dN/d\log a = \text{const}$. The common envelope phase is treated in the standard way based on the energy conservation (Postnov & Yungelson 2006) with the efficiency $\alpha_{\text{CE}} = 0.5$. The calculations were normalized to the galactic star formation rate 3 $M_\odot$ per year, with a binary fraction of 50 per cent. The maximum mass of a main-sequence star that forms a NS in the collapse is set to 30 $M_\odot$, and the maximum mass of a NS is assumed to be 2 $M_\odot$. No hypercritical accretion on to a NS is allowed, as is assumed to be possible in the scenario by Brown (1995). We have also carefully taken into account the rotational evolution of magnetized compact stars, as described in detail in Lipunov (1992) and Lipunov, Postnov & Prokhorov (1996), assuming no NS magnetic field decay.

The galactic DNS merging rate is shown in Fig. 2 as a function of the kick parameter $v_0$ and assuming random central kicks. The calculations were performed for two assumptions about kicks: (i) when the formation of a NS is always accompanied by a kick (we refer to this scenario as kick type A); (ii) when the kick is non-zero during the formation of a NS only in binaries starting out from...
Figure 2. Galactic DNS coalescence rate versus the kick parameter $v_0$ assuming random central kicks. An almost exponential decay with $v_0$ is seen for $v_0 > 100$ km s$^{-1}$ for kick type A, while the decrease in the rate is smaller for kick type B.

Figure 3 shows the relative change in the DNS merging rate with allowance for the NS spin–kick alignment with different values of the kick confinement angle $\theta$ for two kick models. It is seen that tight alignment (small $\theta$) generally reduces the DNS merging rate, with the effect being especially strong for large kick velocity amplitudes. Such a decrease relative to calculations with random kicks is clear because the NS spin–kick correlation excludes kicks in the binary orbital plane, which, if directed opposite to the orbital velocity, can additionally bind the post-explosion binary system.

(i) In close binaries, tidal interactions tend to rapidly align the angular momentum vector of the normal star with the orbital angular momentum. To spin up the NS rotation to observed ms periods (in binary ms pulsars), a modest amount of matter ($\sim 0.1 M_\odot$) should be accreted by the NS. This amount is sufficient to align the NS rotation with the orbital angular momentum. So, if NS1 accreted matter before the second SN explosion, both the NS1 and the secondary component’s spins should most likely be aligned with the orbital angular momentum (see the discussion in Wang et al. 2006). Note that the NS1 spin tends to align with the orbital angular momentum even if NS1 does not accrete matter but spins down by the propeller mechanism before the second SN explosion, as in that case very strong currents must flow through its polar cap and the alignment torque can be as strong as during accretion. So, in close binaries the NS1 remains orbit-misaligned prior to the second SN explosion only in rare occasions where the secondary collapses shortly after the first SN in the binary. If both NS1 and the secondary were aligned with orbital angular momentum before the second SN explosion, both NS1 and NS2 would be equally misaligned with the orbital angular momentum ($\Psi_1$) after SN2 with a kick.

(ii) In sufficiently wide binaries, when tidal interactions between the components are inefficient, the orientation of the NS1 spin and the secondary’s spin vector may remain unchanged until the SN2 explosion, after which the orbital angular momentum vector changes
Figure 4. NS spin–orbit misalignment ($\cos \Psi$) in coalescing DNSs for kick type A with $v_0 = 100 \text{ km s}^{-1}$ (upper row), $v_0 = 200 \text{ km s}^{-1}$ (middle row) and $v_0 = 400 \text{ km s}^{-1}$ (bottom row), and different NS spin–kick alignment angles $\theta$. Left panels: the NS1 and secondary component’s spins aligned with the orbital angular momentum prior to the SN2 explosion (the case of close binaries). Right panels: the NS1 and secondary component’s spins aligned with the original binary’s orbital angular momentum prior to the SN2 explosion.

again because of the NS2 kick. So, in this case we would expect two coaxial NSs with spins misaligned by angle $\Psi_1$ or $\Psi_2$, depending on the strength of tidal interaction (weak or strong, respectively) acting between two SN explosions in the binary system.

From the above, we conclude that the components of a DNS can have coaxial spins misaligned with the orbit by angles $\Psi_1$ or $\Psi_2$, depending on the strength of tidal interaction (weak or strong, respectively) acting between two SN explosions in the binary system.
It is, of course, possible that the spins of the components remain misaligned by some angle depending on the degree of the spin–orbit interaction of the secondary prior to the collapse. For example, the NS1 spin may maintain its original direction in space, while the secondary component before the collapse may have become aligned with the orbital angular momentum. Thus, in the resulting DNS, the spin–orbit misalignment angle of the older NS will be $\Psi_2$, while that of the younger NS will be $\Psi_1$. In this sense, angles $\Psi_1$ and $\Psi_2$ should be considered as limiting cases.

In our population synthesis simulations, we take into account the spin alignment effects discussed here. In Figs 4 and 5 we show the distributions calculated between spins of the components and the
The mean for large kicks 300–400 km s\(^{-1}\) is much narrower distributions (see also Kalogera 2000). The mean spin–kick velocity alignment, may have important implications for gravitational wave studies. First, the tight spin–orbit misalignment angles have uncertainties in the inferred spin–orbit misalignment angles have not allowed firm conclusions to be made yet.

4 CONCLUSIONS

We have shown that the spin-velocity correlation observed in radio pulsars, suggesting NS spin–kick velocity alignment, may have important implications for gravitational wave studies. First, the tight alignment reduces the galactic rate of DNS coalescence (especially for large kicks 300–400 km s\(^{-1}\)) relative to models with random kicks. Secondly, the spin–kick correlation results in a specific distribution of NS spin–orbit misalignments. In turn, an analysis of the NS spin–orbit misalignments inferred from gravitational wave signals during DNS merging can potentially be used to put independent bounds on the still elusive nature of NS kicks.

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REFERENCES

Abbott B. et al., 2007, preprint (arXiv:0704.3368)
Apostolatos T. A., Cutler C., Sussman G. J., Thorne K. S., 1994, Phys. Rev. D, 49, 6274
Bailes M., 1988, A&A, 202, 109
Belczynski K., Kalogera V., 2001, ApJ, 550, 183
Belczynski K., Kalogera V., Bulik T., 2002, ApJ, 572, 407
Bhattacharya D., van den Heuvel E. P. J., 1991, Phys. Rep., 203, 1
Brown E. G., 1995, ApJ, 440, 270
Dewi J. D. M., Podsiadlowski Ph., Pols O. R., 2005, MNRS, 363, 71
Dewi J. D. M., Podsiadlowski Ph., Sana A., 2006, MNRS, 368, 1742
Grishchuk L. P., Lipunov V. M., Postnov K. A., Prokhorov M. E., Sathyaprakash S., 2001, Phys.-Usp., 44, 1 (astro-ph/0008481)
Helfand D. J., Gottlieb E. V., Halpern J. P., 2001, ApJ, 556, 380
Hills J. G., 1983, ApJ, 267, 322
Hobbs G., Lorimer D. R., Lyne A. G., Kramer M., 2005, MNRS, 360, 974
Johnston S., Hobbs G., Vigelands S., Kramer M., Weisberg J. M., Lyne A. G., 2005, MNRS, 364, 1397
Johnston S., Kramer M., Karastergiou A., Hobbs G., Ord S., Wallman J., 2007, MNRS, 381, 1625
Kalogera V., 2000, ApJ, 541, 319
Kalogera V., Belczynski K., Kim C., O’Shaughnessy R., Willems B., 2007, Phys. Rep., 442, 75
Kargaltsev O., Pavlov G. G., Garmire G. P., 2007, ApJ, 660, 1413
Lai D., 2004, in Hoflich P., Kumar P., Wheeler J. C., eds, Cosmic Explosions in Three Dimensions: Asymmetries in Supernovae and Gamma-ray Bursts, Cambridge Univ. Press, Cambridge, p. 276
Lipunov V. M., 1992, Astrophysics of Neutron Stars. Springer-Verlag, Berlin
Lipunov V. M., Postnov K. A., Prokhorov M. E., 1996, in Sanyarov R. A., ed., The Scenario Machine: Binary Star Population Synthesis. Harwood Academic, Amsterdam (arXiv:0704.1387)
Lipunov V. M., Postnov K. A., Prokhorov M. E., 1997, MNRS, 288, 245
Ng C.-Y., Romani R. W., 2007, ApJ, 660, 1357
Pfalz E., Rappaport S., Podsiadlowski P., Spruit H., 2002, ApJ, 574, 364
Podsiadlowski P., RANGER N., POElaERAND A. J. T., Rappaport S., Heger A., Pfahl E., 2004, ApJ, 612, 1044
Portegies Zwart S. F., Ungelson L. R., 1998, A&A, 332, 173
Postnov K. A., Prokhorov M. E., 1998, Astron. Lett., 24, 586
Postnov K. A., Ungelson L. R., 2006, Living Reviews in Relativity, 9, 6
Rankin J., 2007, ApJ, 664, 443
Spruit H. C., Phinney E. S., 1998, Nat, 393, 139
van den Heuvel E. P. J., 2004, in Schönheller V., Lichtig G., Winkler C., eds, The Scenario Machine: Binary Star Population Synthesis. Harwood Academic, Amsterdam (arXiv:0704.1387)
van den Heuvel E. P. J., 2007, in AIP Conf. Proc. Vol. 924, The Multicolored Landscape of Compact Objects and Their Explosive Origins. Am. Inst. Phys., New York, p. 598
Wang C., Lai D., Han J. L., 2006, ApJ, 639, 1007
Wang C., Lai D., Han J. L., 2007, ApJ, 656, 399
Zahn J.-P., 1977, A&A, 57, 383

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