Chin. J. Astron. Astrophys. Vol. 6 (2006), **Suppl. 2**, 241–247
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

Neutron Star Kicks: Mechanisms and Observational Constraints

Dong Lai[1,2] ⋆, Chen Wang[1] and JinLin Han[1]

[1] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
[2] Department of Astronomy, Cornell University, Ithaca, NY 14853, USA

Abstract Observations over the last decade have shown that neutron stars (NSs) receive a kick velocity (of order a hundred to a thousand $\mathrm{km\,s^{-1}}$) at birth. The physical origin of the kicks and the related supernova asymmetry is an unsolved problem. We study observational constraints on kicks for isolated pulsars and for neutron stars in binary systems. For several young pulsars, X-ray observations of compact nebulae showed that pulsar proper motion is aligned with the spin direction as defined by the symmetry axis of the nebula. Such alignment is also seen from a new analysis of radio polarization data for a large number of pulsars. On the other hand, for various NS binaries (including double NS systems, binaries with massive main-sequence star companion and binaries with massive white-dwarf companion), we find that the kick velocity is misaligned with the the NS spin axis in a number of systems, and the NS spin period (when available) in these systems is generally longer than several hundreds milliseconds. These observational constraints suggest that the kick timescale is hundreds of milliseconds to 1s, so that spin-kick alignment or misalignment can be obtained depending on the initial spin period of the NS. We discuss the implication of our result for various NS kick mechanisms.

Key words: stars: kinematics — pulsars: general — stars: neutron — stars: rotation — binaries: close

1 INTRODUCTION

It has long been recognized that neutron stars (NSs) may have received large kick velocities at birth. First, the measured NS velocities, several hundreds $\mathrm{km\,s^{-1}}$, are much larger than their progenitors' velocities (see Section 2 below). Second, while large space velocities can in principle be accounted for by binary break-up many observed characteristics of NS binaries can be explained only if there is a finite kick at NS birth (see Section 3). In addition, direct observations of many nearby supernovae show that supernova explosions are not spherically symmetric, consistent with the existence of NS kicks.

While the evidence for NS kicks is unequivocal, the physical origin remains unclear. The proposed mechanisms include hydrodynamical instabilities in the collapsed supernova core, asymmetric neutrino emission induced by super strong magnetic fields and post-natal electromagnetic boost (see Lai 2004; Janka et al. 2004 and references therein; see Section 4). One of the reasons that it has been difficult to spin down the kick mechanisms is the lack of correlation between NS velocity and the other properties of NSs. The situation has changed with the recent X-ray observations of the compact X-ray nebulae of several young pulsars, which indicate an approximate alignment between the pulsar proper motion and its spin axis (see Lai et al. 2001; Ng & Romani 2004). For a number of NS binary systems, possible spin-kick relationship can be probed from the observed binary property (e.g. geodetic precession; see Section 3). It is therefore useful to see whether a consistent picture about NS kicks can be obtained from the two sets of observational constraints.

⋆ E-mail: `dong@astro.cornell.edu`

In this paper, we seek empirical constraints on the kick mechanism. We are particularly interested in the possible alignment/misalignment between the kick and the angular momentum of the NS, and how such alignment/misalignment depends on the NS initial spin period. In Section 2, we summarize and update relevant observational data on isolated pulsars. In addition to several young pulsars for which the spin axis can be measured from the pulsar wind nebula, one can also constrain the spin axis from well-calibrated polarization data. We critically assess the information from such polarization study and demonstrate a correlation between spin axis and proper motion for these pulsars. In Section 3 we discuss constraints on NS kicks in various types of NS binaries. In addition to several well-studied NS/NS binaries, we also consider other types of binaries, such as pulsar/main-sequence and pulsar/white-dwarf binaries. We show that in general, the kick direction is misaligned with the NS spin axis. We discuss the implications of our findings in Section 4.

2 KICKS IN ISOLATED PULSARS

By now a number of statistical studies on pulsar velocities have been carried out (e.g., Lyne & Lorimer 1994; Arzoumanian et al. 2002; Hobbs et al. 2005). These studies give a mean birth velocity $100-500\ \mathrm{km\,s^{-1}}$, with possibly a significant population having $V > 1000\ \mathrm{km\,s^{-1}}$. Arzoumanian et al. (2002) favor a bimodal pulsar velocity distribution, with peaks around $100\ \mathrm{km\,s^{-1}}$ and $500\ \mathrm{km\,s^{-1}}$. An analysis of the velocities of 14 pulsars with parallax by Chatterjee et al. (2006) yields a similar result (with $\sigma_v \simeq 100\ \mathrm{km\,s^{-1}}$ and $300\ \mathrm{km\,s^{-1}}$). Another recent study of 73 young pulsars by Hobbs et al. (2005) (see also Faucher-Giguere & Kaspi 2006) gives a mean 3D pulsar velocity of $400\ \mathrm{km\,s^{-1}}$, consistent with a single Gaussian distribution.

Despite some early claims, there is currently no statistically significant correlation between the pulsar velocity and the period or the dipole magnetic field strength (as inferred from P, $\dot{P}$) (e.g., Lorimer et al. 1995). This lack of correlation is not surprising given the large systematic error in the analysis. From a physics point of view, it is also not surprising: (1) The observed spin period for young pulsars is 10 ms or longer, much too slow compared to the breakup rotation rate of a NS (period 1 ms or less); such a slow rotation would not play any dynamically important role in the supernova explosion. (2) The currently observed dipole field of pulsars is $10^{12}-10^{14}$ G, much weaker than the $10^{15}-10^{16}$ G fields required for magnetic field to affect the explosion dynamics or neutrino emission in proto-NSs (see Section 4).

Spin-Kick Correction from Study of Pulsar Wind Nebulae: Recent *Chandra* observations of the pulsar wind nebulae (PWN) have provided evidence for spin-kick alignment for several pulsars (see Lai et al. 2001; Ng & Romani 2004). In particular, the X-ray nebulae of the Crab and Vela pulsars have a two-sided asymmetric jet at a position angle coinciding with the position angle of the pulsar's proper motion. The symmetric morphology of the nebula with respect to the jet direction strongly suggests that the jet is along the pulsar's spin axis. For Crab, the angle between the spin axis and the proper motion is $\Delta\Psi = 12^\circ \pm 10^\circ$, and for Vela $9^\circ \pm 4^\circ$. Other cases include: PSR J0538+2817, $\Delta\Psi = 7^\circ \pm 9^\circ$, with an estimated initial spin period of $P_{\rm init} = 139$ ms; PSR B1706–44, $\Delta\Psi = 15^\circ \pm 11^\circ$, $P_{\rm init} \simeq 76$ ms; PSR B1951+32, $\Delta\Psi = 13^\circ \pm 9^\circ$, $P_{\rm init} \simeq 27$ ms; PSR J1124–5916, $\Delta\Psi = 22^\circ \pm 7^\circ$ and $P_{\rm init} \simeq 65$ ms. We note that for three of the pulsars discussed above, the spin axis can be measured from the intrinsic polarization profile (see below). This gives a consistent spin-velocity angle as the measurement from PWN, after one takes into account of the possible orthogonal mode emission from pulsars.

Spin-Kick Correlation from Polarization Study: Another way of constraining the pulsar spin axis is through radio polarization profile. The polarization angle of linearly polarized emission from pulsars is related to the dipole magnetic field geometry of the emission region of a NS. At the pulse center, the line of sight and the spin axis are in the same plane as the curved magnetic field line. This provides a constraint of the projected spin axis on the plane of the sky. Note that radio emission from pulsars could have linear polarization parallel or orthogonal to magnetic field. If spin-kick aligns well, the difference between intrinsic polarization angle (IPA) and proper motion could be either 0° (for normal mode emission) or 90° (for orthogonal mode emission).

Previous investigations of spin-velocity correlation based on polarization data have given inconsistent results (e.g., Deshpande et al. 1999). With the new measurements of proper motions of 233 pulsars (Hobbs et al. 2005), it is useful to re-examine the spin-velocity correlation from polarization data available. To this end, we select normal pulsars (with characteristic age less than a few $\times 10^7$ yr) for which the uncertainty

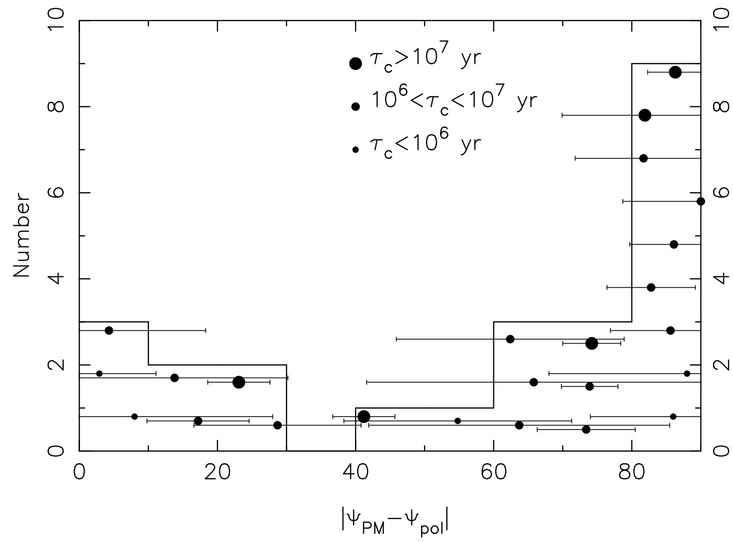

Fig. 1 The number distribution of the angular difference between the proper motion and intrinsic polarization direction for 24 pulsars. Each pulsar is represented by a symbol specified by the characteristic age of the pulsar.

of position angle of the proper motion is less than 15 degree. We then search the literature for observations of their polarization properties and rotation measures. Note that many polarization profiles were not well-calibrated in the polarization angle, and some observations have serious (10% or more) instrumental effect. In our analysis, we use high frequency ($\gtrsim$1.4 GHz) data; low frequency polarization observations are excluded because of the large-uncertainties of measured polarization angle from even a small uncertainty of Faraday rotations. The polarization profiles we use are mostly from Parkes observations, for which we know that their polarization angles were well calibrated. We take the polarization angle at the maximum sweeping rate or about the pulse center, and calculate IPA with the observation frequency and the pulsar rotation measures. We discard the pulsars when the errors of the calculated IPA are greater than 20 degrees. Finally, we obtain the difference between the direction of proper motion and IPA, and remove any object with uncertainty of the difference greater than 25 degree. After the above procedures, 24 pulsars are left (see Fig. 1).

Figure 1 shows the number distribution of the angular difference $|\Psi_{\rm PM} - \Psi_{\rm pol}|$. A significant peak appears near $90°$, and another peak near $0°$ is also visible. Since the polarization direction is either parallel or perpendicular to the spin axis, the data therefore indicate a significant correlation between the spin and velocity. Given the result of PWN studies (Section 2), the most likely cause for the two peaks is that spin and kick are aligned in many cases, and different pulsars prefer to emit in one of the two orthogonal modes. Obviously, in this interpretation, intrinsic polarization emission favors perpendicular-mode emission for most pulsars. Similar results were also obtained recently by Johnston et al. (2005) (see Wang et al. 2006).

3 KICKS IN BINARY NEUTRON STARS

Useful constraint on NS kicks (both magnitude and direction) can also be obtained from binary pulsar systems, including NS/NS binaries, NS/Main-Sequence Star (MS) binaries, NS/Massive white dwarf (MWD) binaries and high-mass X-ray binaries (HMXBs).

3.1 Method and Assumptions

The basic procedure for obtaining the constraint is as follows: In the pre-supernova (SN) binary system, we have two stars with mass [1] $m_{\rm Ai}$ and $m_{\rm Bi}$ in a circular orbit (eccentricity $e_{\rm i} = 0$) with semi-major axis

[1] The subscript “i” specifies parameters before SN, “f” after SN, and “0” currently observed parameters.

$a_{\rm i}$. Star B is a helium star ready to explode, and its mass $m_{\rm Bi}=m_{\rm He}$ is constrained within the range 2.1–8.0 $M_\odot$ (the lower limit corresponds to the lowest mass for which a He star is expected to form a NS instead of a white dwarf, while the upper limit corresponds to the highest mass for which a He star is expected to form a NS rather than a black hole). Star A is either a NS, a massive MS or a massive WD. As B explodes in a SN (the explosion can be considered instantaneous compared to the orbital period), it leaves behind a NS with mass $m_{\rm B}<m_{\rm Bi}$, and because of the asymmetry in the explosion or in the neutrino emission, the NS (in its rest frame) receives a kick velocity $\boldsymbol{V}_k$. The angle between $\boldsymbol{V}_k$ and the pre-SN angular momentum $\boldsymbol{L}_i$ is γ. To a good approximation, star A is assumed to be unaffected by the explosion of B, i.e., its mass $m_{\rm A}=m_{\rm Ai}$ after the SN, its post-SN velocity equals the pre-SN velocity. Because of the mass loss and kick in the explosion, the post-SN orbit (with semi-major axis $a_{\rm f}$) will in general be eccentric ($e_{\rm f}\neq 0$), and the orbital angular momentum $\boldsymbol{L}_f$ will be misaligned relative to $\boldsymbol{L}_i$ by an angle θ. Using angular momentum conservation and energy conservation, we find

$$\boldsymbol{V}_{\rm k}^2=\frac{GM_{\rm f}}{a_{\rm f}}\left[2\xi-1+\xi\eta^{-1}-2(1-e_{\rm f}^2)^{1/2}\xi^{3/2}\eta^{-1/2}\cos\theta\right], \tag{1}$$

$$\cos^2\gamma=\frac{\xi^2(1-e_{\rm f}^2)\sin^2\theta}{2\xi-1+\xi\eta^{-1}-2(1-e_{\rm f}^2)^{1/2}\xi^{3/2}\eta^{-1/2}\cos\theta}, \tag{2}$$

where $M_{\rm f}=m_{\rm A}+m_{\rm B}$, $M_{\rm i}=m_A+m_{\rm Bi}$, $\eta=M_{\rm f}/M_{\rm i}$ (with $\eta<1$), and $\xi=a_{\rm f}/a_{\rm i}$, which satisfies $(1+e_{\rm f})^{-1}<\xi<(1-e_{\rm f})^{-1}$.

The assumptions leading to Euqations (1)-(2) are fairly standard, and similar equations have been used in numerous previous studies. To obtain useful constraint on the kick-spin correlation, we need to make further assumptions about the rotations of the two stars: (1) In the pre-SN binary, the assumption of circular orbit made above is justified from the strong tidal interaction and/or mass transfer, which also guarantee that spin angular momentum vectors of the two stars are aligned with the orbital angular momentum vector (i.e., $\boldsymbol{S}_{Ai}\parallel\boldsymbol{S}_{Bi}\parallel\boldsymbol{L}_i$). (2) In deriving Equations (1) and (2), we have assumed that the SN of star B (He star) does not affect the mass and motion of star A. We also assume that the spin direction of star A is unchanged during the explosion, i.e. $\boldsymbol{S}_{Af}\parallel\boldsymbol{S}_{Ai}$. These assumptions can be justified (see Wang et al. 2006). Thus the angle θ between $\boldsymbol{L}_i$ and $\boldsymbol{L}_f$ is equal to the angle between $\boldsymbol{L}_f$ and $\boldsymbol{S}_{Af}$, which can be constrained observationally in several systems.

Note that the post-SN binary may continue to evolve, so the currently observed orbital elements $a_0,\ e_0$ may not be the same as $a_{\rm f},\ e_{\rm f}$. Depending on the type of systems, the evolution may be driven by gravitational radiation or tidal effects.

3.2 Results

NS/NS Binaries: Currently there are 9 observed NS/NS binary systems observed in our Galaxy: 7 are listed in Stairs (2004), plus PSR J1756–2251 (Faulkner et al. 2005) and possibly J1906+0746 (Lorimer et al. 2006). They consist of a recycled millisecond pulsar (A) and a second-born NS (B) which, in most cases, is not visible as a radio pulsar (with the exception of the double pulsar system, PSR J0737–3039; also, J1906+0746 appears to be the second-born NS). For PSR J1913+16 and PSR B1534+12, geodetic precession has been observed, providing constraint on θ. For all these systems, it is found that modest kicks which are misaligned with the pre-SN orbital angular momentum are required to produce the spin-orbit characteristics (orbital period, eccentricty and, in two systems, θ) of these systems.

Pulsar/MS Binaries: There are three published pulsar/MS binaries. Such systems evolve from He-star/MS binaries (which in turn evolves from MS/MS binaries) when the He star explodes in a SN to form a NS. After the explosion, the pulsar/MS binary may further evolve under tidal interaction if the orbit is sufficiently compact. Of most interest is PSR J0045–7319, which contains a 0.926 s pulsar in an orbit with a B star companion. Timing observations revealed the effects of classical spin-orbit coupling due to the rapid rotation of the B star, including periastron advance and precession of the orbital plane (Kaspi et al. 1996; see also Lai et al. 1995). This constrains θ and implies a spin-mislaigned kick. Also, the initial spin of the pulsar can be constrained using the observed tidal-driven orbital decay.

Young pulsars with massive white dwarf companions: Such systems are thought to evolve from binaries in which both stars are initially less massive than the critical mass required to produce a NS. The initially more massive star transfers mass to its companion before becoming a WD. If sufficient matter can be accreted by the initially low mass star, it will exceed the critical mass and produce a NS. Should the system remain bound, an eccentric binary with a young NS and a MWD companion will be produced. Two such systems are known. For one of these systems (PSR J1141−6545), misaligned kick is required; for the other system, only weak constraint on the kick can be obtained (Wang et al. 2006).

High-Mass X-Ray Binaries: A HMXB consists of a NS, which often appears as an X-ray pulsar, and a massive stellar companion (e.g. a Be star). Of the ~ 130 known HMXBs, about 20 have well-constrained orbital elements, mostly determined from the timing of the X-ray pulsars. There are three classes of HMXBs, distinguished by their orbital parameters: (1) Systems with $P_{\rm orb} < 10$ days and $e < 0.1$: The low orbit period and low eccentricity indicate that tidal circularization has played a significant role. So one cannot obtain constraint on NS kicks from the observed orbital parameters. (2) Be X-ray binaries with moderately wide orbits and high eccentricities ($P_{\rm orb} \sim 20 - 100$ days, $e \sim 0.3 - 0.5$). The high eccentricities indicates these systems have received large kicks, with a mean speed of $\sim 300\,{\rm km\,s^{-1}}$ (see Pfahl et al. 2002). (3) Possibly another class of Be X-ray binaries has recently been identified by Pfahl et al. (2002). These systems are distinguished from the well-known Be X-ray binaries by their wide orbits (all have $P_{\rm orb} > 30$ days) and fairly low eccentricities ($e < 0.2$). The NSs born in these systems apparently have received only a small kick, $< 50\,{\rm km\,s^{-1}}$.

4 DISCUSSION

4.1 Tentative Inference from Observational Data

Our analysis of the velocity-spin correlation for isolated pulsars (Section 2) shows that kick is aligned with spin axis for many (but most likely not all) pulsars (see Fig. 1). Of particular interest is the fact that for pulsars with estimated initial spin periods (when such estimates can be made) less than $\sim$ 200 ms, the kick is apparently aligned with the spin axis to within the error of measurements (typically $\pm 10^\circ$). With the exception of PSR J0538+281 (for which $P_{\rm init} \sim 140$ ms), the initial spin periods of these pulsars are all less than ~ 70 ms. On the other hand, our analysis of SN kicks in NS binaries based on the observed spin-orbital property of various NS binaries (Section 3) shows that in a number of systems, the kick must not be aligned with the spin axis of the *NS progenitor*. How can we reconcile this conclusion with the apparent spin-kick alignment for many isolated pulsars?

One possibility is that although the kick $\boldsymbol{V}_k$ is misaligned with the spin axis (denoted by $\boldsymbol{S}_{Bi}$ in Section 3) of the He star, it may still be aligned with the spin axis of the NS, since the NS may get most of its angular momentum from off-centered kicks rather than from its He star progenitor (Spruit & Phinney 1998). However, in the absence of any "primordial" angular momentum from the progenitor, a kick (of any duration) displaced by a distance s from the center, produces a spin of $\simeq 12\,(\boldsymbol{V}_{\rm k}/300\,{\rm km\,s^{-1}})(s/10\,{\rm km})$ Hz, with the spin axis necessarily perpendicular to the velocity direction. If the kick is the result of many thrusts on the proto-NS (Spruit & Phinney 1998), the relative direction of the net kick and spin depends on how the orientation of each thrust is correlated with each other. Spin-kick alignment is possible in some circumstances, but is by no means a generic prediction of the "multiple thrusts" scenario. If the kick direction is not aligned with the He star spin (as we show for many NS binaries in Section 3), it will not be aligned with the NS spin in general, regardless of the origin of the NS spin.

An important clue comes from the PSR 0045–7319/B-star system: The kick imparted to the pulsar at its birth is misaligned with its spin axis, and the initial spin period has been constrained to be $P_{\rm init} > 0.5$ s. Also, for PSR 0737–3039 (with pulsar B spin period $P_0 = 2.77$ s) and many other NS/NS binaries, as well as for the PSR J1141–6545/MWD system (with $P_0 = 0.39$ s), the kick is misaligned with the spin axis. In addition, for the PSR J1740–3053/MS (with $P_0 = 0.57$ s) system, the kick and spin may be misaligned.

Combining these kick constraints obtained from NS binaries with the information we have about kicks in isolated pulsars, we are led to the following tentative suggestion: When the NS initial spin period is less than a few $\times 100$ ms, the kick will be aligned the the spin axis; otherwise, the kick will in general not be aligned with the spin axis, except by chance. This suggestion, by no means definitive, is consistent with all the observational data on NS kicks in isolated pulsars and in NS binaries which have analyzed/summarized in Section 2 and Section 3.

4.2 Implications for Kick Mechanisms

Many mechanisms for NS kicks have been suggested or studied. They generally fall into the following categories (e.g., Lai 2004; Janka et al. 2004): (i) *Hydrodynamically driven kicks* in which the SN explosion is asymmetric (with the explosion stronger in one direction than the other directions), and the NS receives a kick according to momentum conservation. Large-scale convections in the neutrino-heated mantle behind the stalled shock (at ~ 100 km) may naturally lead to such asymmetric explosion, particularly when the delay between core bounce and shock revival is sufficiently long to allow for small-scale convective eddies to merge into bigger ones (e.g., Scheck et al. 2004; Foglizzo et al. 2005). Pre-SN asymmetric perturbations due to convective O-Si burning, amplified during core collapse (Lai & Goldreich 2000), may also play a role (Goldreich et al. 1996; Fryer 2004). The kick timescale ranges from 10 s to 100's ms. Obviously, detailed calculations of this class of mechanisms are still uncertain — such a calculation/simulation is an integral part of the general problem of SN explosion mechanism. (ii) *Magnetic-Neutrino Driven kicks* rely on asymmetric neutrino emission induced by strong magnetic fields. This could arise because the strong magnetic field modifies the neutrino opacities either through standard weak-interaction physics (e.g. Arras & Lai 1999) or through nonstandard physics (e.g., Fuller et al. 2003). It could also arise from the dynamical effect of the magnetic field on the proto-NS (e.g., the B field can affect the neutrino-driven convection/instabilities, and thus creating dark or hot neutrino spots). All these effects are important only when the magnetic field of the proto-NS is stronger than 10^{15} G. The kick timescales are of order the neutrino diffusion time, a few seconds. (iii) *Electromagnetically driven kicks* involve radiation from off-centered rotating dipole, which, for appropriate dipole orientation/displacement, imparts a gradual acceleration to the pulsar along its spin axis (see Lai et al. 2001). This effect is important only if the NS initial period is $\lesssim 2$ ms. The kick time is of order the initial spin-down time ($\simeq 10^7$ s for $B = 10^{13}$ G and $P_{\rm init} = 14$ ms). (iv) Other mechanisms are possible if the collapsing iron core has large angular momentum. For example, the combination of rapid rotation and magnetic field may lead to bipolar jets from the SN, and a slight asymmetry between the two jets will lead to a large kick. Another mechanism could be that, if a rapidly rotating core fragments into a double proto-NS binary (current numerical simulation indicates this is unlikely), the explosion of the lighter proto-NS (after mass transfer) could give the remaining NS a kick.

It is of interest to use observations to constrain or rule out some of these mechanisms. Since the initial spin period of radio pulsars is $\gg 1$ ms, (iii) and (iv) appear unlikely in general. The observed dipole magnetic field of most radio pulsars lies in the range $10^{12} - 10^{13}$ G, but it is not clear whether most proto-NSs can have (even transient) magnetic fields stronger than 10^{14} G. So we cannot easily rule out (ii).

Regarding spin-kick alignment/misalignment, the crucial point is the ratio between the initial spin period $P_{\rm init}$ and kick timescale $\tau_{\rm kick}$. In hydrodynamically driven kicks (i) and magnetic-neutrino driven kicks (ii), the primary thrust to the NS does not depend on the NS spin axis. But the net kick will be affected by rotational averaging if $P_{\rm init}$ is much less than $\tau_{\rm kick}$. Let V_0 be the kick velocity that the NS attains in the case of zero rotation, and θ_k be the angle between the primary asymmetry and the rotation axis. The expected components of kick along the rotation axis and perpendicular to it are (for $\tau_{\rm kick} \gg P_{\rm init}$) $V_{\rm kick\parallel} = V_0 \cos\theta_k$ and $V_{\rm kick\perp} \sim (\sqrt{2}\,P/2\pi\,\tau_{\rm kick})V_0 \sin\theta_k$. Thus the angle γ between the kick vector $\boldsymbol{V}_{\rm kick}$ and the spin axis is given by $\tan\gamma \sim 0.2(P_{\rm init}/\tau_{\rm kick})\tan\theta_k$. Typically, the spin-kick alignment will be achieved when $\tau_{\rm kick} \gg P_{\rm init}$. The observed spin-kick alignment for $P_{\rm init} \lesssim 100$'s ms discussed in Section 4.1 therefore suggests that $\tau_{\rm kick}$ lies between hundreds of ms to 1s. Such a kick timescale is consistent with magnetic-neutrino driven mechanisms or hydrodynamical mechanisms with long-delayed SN explosions.

Obviously, this conclusion is far from definitive. For example, since the primary thrust may be applied at a distance larger than the NS radius, a somewhat more stringent condition on $P_{\rm init}$ is required to produce spin-kick alignment (see Lai et al. 2001). In other words, the inequality $P_{\rm init} \ll \tau_{\rm kick}$ is a necessary (but not sufficient) condition for spin-kick alignment. Also, an initial spin period of order 100's ms could be generated by the SN kick itself (see above). We have argued that a kick-induced spin without “primordial” angular momentum (i.e. from the progenitor) would not in general give rise to spin-velocity alignment. The situation may be different with even a modest primordial spin.

Acknowledgements This work is supported by National Natural Science Foundation of China (10328305, 1025313 and 10473015). DL has also been supported in part by NSF and NASA.

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