Pulsar spin–velocity alignment from single and binary neutron star progenitors

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ABSTRACT

The role of binary progenitors of neutron stars (NSs) in the apparent distribution of space velocities and spin–velocity alignment observed in young pulsars is studied. We performed a Monte Carlo synthesis of pulsar populations originated from single and binary stars with different assumptions about the NS natal kick (kick–spin alignment, kick amplitude and kick reduction in electron-capture supernovae in binary progenitors with initial main-sequence masses from the range 8–11 M⊙ which experienced mass exchange due to Roche lobe overflow). The calculated spin–velocity alignment in pulsars is compared with data inferred from radio polarization measurements. The observed space velocity of pulsars is found to be mostly affected by the natal kick velocity form and its amplitude; the fraction of binaries is not important here for reasonably large kicks. The natal kick–spin alignment is found to strongly affect the spin–velocity correlation of pulsars. Comparison with the observed pulsar spin–velocity angles favours a sizeable fraction of binary progenitors and kick–spin angles ∼5°–20°.

Key words: stars: neutron – pulsars: general – X-rays: binaries.

1 INTRODUCTION

Neutron stars (NSs) resulting from core collapses of massive stars are observed in very different astrophysical sources [radio pulsars (PSRs), compact central objects in supernova (SN) remnants, soft gamma-ray repeaters, anomalous X-ray pulsars, cooling radio-quiet NSs, X-ray binaries, etc.], and new observational appearances of NSs are discovered nearly every few years [rotating radio transients are one of the latest examples; for a comprehensive review on recent studies in this field, see e.g. the conference proceedings (Bassa et al. 2008)]. Determination of the birth properties of NSs is crucial to understand the physics of SNe and to model the evolution of NSs. For a given equation of state of the NS matter, the main physical parameters of a newborn NS, which determine its evolution and observational appearance, include its mass, spin period, surface magnetic field and the initial space velocity. The situation is more complicated when a NS is formed in a binary system. Then, the subsequent evolution of the NS will also be determined by the binary orbital parameters and the evolutionary state of the secondary component prior to the SN explosion, in addition to the initial conditions of the collapse.

In single radio pulsars, NS space velocities (more precisely, their tangential component) can be measured directly. Using complicated models, one can reconstruct the distribution of the NS birth velocities [see e.g. Faucher-Giguère & Kaspi (2006) and references therein]. The shape of the resulting distribution is still ambiguous. Some authors (Arzoumanian, Chernoff & Cordes 2002) favour a bimodal Maxwellian distribution, some (Hobbs et al. 2005) argue that the data can be explained with a single Maxwellian curve, while others (Faucher-Giguère & Kaspi 2006) prefer single-mode non-Maxwellian distributions. Moreover, the space velocity (in both magnitude and direction) can be correlated with other parameters. In pulsars, one of the best-known correlations is found between the direction of the space velocity vector and the spin axis of the NS. It is well established for the Crab and Vela pulsars and is found in several other objects with well-studied pulsar wind nebulae (Ng & Romani 2004, 2007). Polarimetric measurements of radio pulses also allow us to estimate the angle δ between the spin axis and the NS space velocity direction (Johnston et al. 2005; Rankin 2007). The spin–velocity correlation is firmly established only in young pulsars, since for older ones the motion in the Galactic gravitational potential smears out any initial relation between the NS spin and velocity vectors.

Recently, Johnston et al. (2007) reported new measurements of the angle δ between the spin axis and space velocity direction in 14 radio pulsars. Half of them demonstrate strong alignment, while others do not. New pulsar measurements and observations of pulsar wind nebulae are expected to increase the list of objects with known δ (e.g. Rankin 2007).
The origin of the spin–velocity alignment is usually related to the kick mechanism operating during or immediately after the stellar core collapse. The reason why NSs obtain such large (up to >1000 km s\(^{-1}\)) space velocities remains unknown. Several absolutely different physical mechanisms are discussed (see e.g. the table in Bombsci & Popov 2004, and reviews in Lai, Chernoff & Cordes 2001 and Postnov & Yungelson 2006).

Historically, the first proposed kick mechanism was related to an asymmetric mass ejection during the SN explosion (Shklovskii 1970). Recently, a modification of this mechanism was studied in numerical simulations by Scheck et al. (2004, 2006). In these simulations, large kicks can be recovered, but the direction of the velocity is found to be poorly correlated with the NS spin axis. Nevertheless, in the framework of this mechanism the correlation is possible for small spin periods of newborn NSs (\(P < \)1 ms), as rapid rotation results in averaging of momentum along all directions except the spin vector (Lai et al. 2001), and anisotropies appear not randomly but preferentially along the rotation axis (Scheck et al. 2006).

In some models, the NS kick is related to an asymmetric neutrino emission in a strong magnetic field. The first scenario of this type was proposed by Chugai (1984) (see also the paper by Bisnovatyi-Kogan 1993). Several variants of this mechanism were later discussed by Lai et al. (2001). In the neutrino scenarios, the spin–velocity alignment is possible if the neutrino emission time is longer than the spin period or if the magnetic dipole is initially aligned with the spin axis.

A tight spin–velocity alignment naturally emerges in two other mechanisms: when the kick is due to asymmetry between two oppositely directed matter jets emanating from a newborn NS (Khokhlov et al. 1999; Akiyama et al. 2003), or when a rotating NS with asymmetric (e.g. off-centred) magnetic dipole is gradually accelerated by electromagnetic radiation (the electromagnetic rocket mechanism suggested by Harrison & Tademaru 1975). The spin–velocity alignment may be a consequence of the magneto-rotational SN explosion (Ardeljan, Bisnovatyi-Kogan & Moiseenko 2005).

A perfect orthogonal spin–velocity misalignment is expected in the case of collapsing core fragmentation due to rapid rotation (Berezhzinsky et al. 1988; Imanishiki 1992; Imanishiki & Nadezhdin 1992; Colpi & Wasserburg 2002). However, it is unclear whether this mechanism can be generic for the majority of NSs, since numerical models of stellar evolution suggest rather slow rotation of the stellar core prior to the collapse (Heger, Woosley & Spruit 2005).

If all NSs were originated from isolated progenitors, deviations from the spin–velocity alignment could be related to differences in the kick mechanism or in the NS behaviour immediately after formation (the typical space velocity of massive stars – NS-progenitors, \(\sim\)10–30 km s\(^{-1}\), is much smaller than the NS kick velocities and so cannot significantly affect the relative orientation of the spin and velocity axis; see the results below). This possibility was studied, for example, by Ng & Romani (2007). However, at least half of isolated NSs are expected to be born in binaries so the net space velocity acquired by a NS formed in a binary system should be the sum of the NS natal kick and the orbital velocity of the NS progenitor prior to the binary disruption (plus the velocity of the binary system barycentre). Even if the kick mechanism generates a single-mode velocity distribution, the additional contribution from the progenitor’s orbital motion in the binary system can change its shape. While the effects of the binary progenitor on the observed NS space velocity distribution can be notable only for small kicks (of order or smaller than the orbital velocity of the collapsing star, typically <100 km s\(^{-1}\)), they can appear more pronounced in the NS spin–velocity misalignment. In our previous paper (Postnov & Kuranov 2008), we studied the NS spin–kick velocity correlation effect on binary NS coalescence rates and spin–orbit misalignment of the components. In the present paper, we particularly address the role of binaries in shaping the NS space velocity distribution and their effect on the spin–velocity alignment in observed radio pulsars.

### 2 Population Synthesis Code

For our population synthesis calculations, we use the scenario code, developed at Sternberg Astronomical Institute (see Lipunov, Postnov & Prokhorov 1996; Lipunov et al. 2007 and references therein\(^1\)). The general description of the population synthesis techniques can be found in Popov & Prokhorov (2007).

The standard assumptions about the binary evolution are made: the Salpeter mass function for the primary mass, \(dN/dM_1 \sim M_1^{-2.35}\), the initial semimajor axis distribution in Opik’s form \(dN/d\log a = \text{const}\),

\[
\max \left\{ \frac{10 R_\odot}{R_d(M_1)} \right\} < a < 10^7 R_\odot,
\]

where \(R_d(M_1)\) is the radius of the Roche lobe of the primary component.

Calculations are done for two assumptions about the initial mass ratio \((q = M_2/M_1 < 1)\) distribution: \(dN/dq \sim q^0\) (flat distribution), and the mass ratio distribution \(dN/dq \sim q^2\) which is strongly peaked towards equal masses of the components. The latter choice is related to recent studies by Pinsonneault & Stanek (2006) who found a large fraction of twins among 21 eclipsing massive binaries in the Small Magellanic Cloud. The real initial distribution of binary mass ratio in our Galaxy is still unknown, but the choice of these two limiting cases (the flat one and the one strongly peaked towards equal masses) gives us a flavour of how sensitive are our results to this important initial parameter.

The common envelope phase of the binary evolution is treated in the standard way based on energy conservation (Postnov & Yungelson 2006) with efficiency \(\alpha_{\text{CE}} = 0.5\).

We assume that the kick velocity vector is confined within a cone coaxial with the progenitor’s rotation axis and characterized by the angle \(\theta \leq \pi/2\). We shall consider only central kicks thus ignoring theoretically feasible off-centre kicks simultaneously affecting the NS spin (Postnov & Prokhorov 1998; Spruit &phinney 1998; Wang, Lai & Han 2007).

We made two assumptions about the NS kicks.

(i) Kick type A. It is a single-Maxwellian (for the sake of simplicity) distribution \(f(v) \sim (v^2/v_0^2)^\alpha \exp[-(v/v_0)^2]\), as suggested by pulsar proper motion measurements (Hobbs et al. 2005). The parameter \(v_0\) is varied within the range 100–500 km s\(^{-1}\). For NSs from single progenitors, we always assume this type of the kick.

(ii) Kick type B. It assumes kick type A for NSs from single progenitors and from binary progenitors with maximum masses during the lifetime above \(11 M_\odot\). For NSs from binary progenitors with maximum lifetime masses in the range \(8\)–\(11 M_\odot\) that experienced Roche lobe overflow, in which electron-capture (\(e^-\)capture) core collapse can occur (Podsiadlowski et al. 2004; van den Heuvel 2004, 2007), \(v_0\) is reduced and kept fixed at 30 km s\(^{-1}\).

According to the type of kick assumed, we made calculations for different model populations of NSs, as summarized in Table 1. Model SA means kick type A from single progenitors, BA means

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\(^1\) See the on-line material at http://xray.sai.msu.ru/~mystery/articles/review.
kick type A from binary progenitors, BB means kick type B from binary progenitors, BAS means kick type A and BBS means kick type B from binary progenitors. An isolated NS originating in a binary system acquires both the natal kick velocity and the orbital velocity of the exploding star immediately before the collapse. The result is sensitive to the mutual orientation of the kick and orbital velocities. In Fig. 1, we plot space velocities of NSs calculated for single and binary progenitors in comparison with a purely Maxwellian velocity distribution. As expected, the influence of the orbital velocity in binary progenitors is insignificant for low velocities. It appears quite SN 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 in the binary can happen before the orbit has been tidally circularized. Possible mass transfer phases before the second collapse (such as the common envelope stage and mass accretion on to the neutron star due to Roche lobe overflow at periapsis passages) are assumed to effectively circularize the orbit.

In the absence of mass transfer, the tidal evolution of the orbital eccentricity is treated according to Zahn (1977). When treating the SN explosion in an eccentric binary, the orbital position of the explosion is chosen randomly with a uniform distribution over the mean anomaly.

### 3 RESULTS: THE ROLE OF BINARIES

In this section, we discuss the effect of binary progenitors of NSs on the pulsar space velocities and spin–velocity misalignment. For this purpose, we calculate populations of isolated NSs arising from purely single and binary progenitors (models SA, BB), and populations resulting from equal numbers of single and binary progenitor stars (models BAS, BBS).

#### 3.1 Space velocity of young NSs

First, we consider the NS velocity distributions calculated from isolated and binary progenitors. An isolated NS originating in a binary system acquires both the natal kick velocity and the orbital velocity of the exploding star immediately before the collapse. The result is sensitive to the mutual orientation of the kick and orbital velocities. In Fig. 1, we plot space velocities of NSs calculated for single and binary progenitors in comparison with a purely Maxwellian velocity distribution. As expected, the influence of the orbital velocity in binary progenitors is insignificant for large kick velocities ($v_p \approx 300 \text{ km s}^{-1}$, as was adopted in this plot). However, for kick type B, where a notable fraction of NSs in binaries received a reduced kick, the emerging NS velocity distribution slightly deviates from the pure Maxwellian law at low velocities. It appears quite

![Figure 1. The space velocity distribution of isolated young NSs (pulsars). The results are shown for model SA (black squares), model BB (black triangles) and model BBS (grey upside-down triangles), with $v_p = 300 \text{ km s}^{-1}$. A pure Maxwellian distribution (filled circles) is plotted for comparison. Note a small deviation from the pure Maxwellian distribution at low velocities for models BB and BBS.](https://academic.oup.com/mnras/article-abstract/395/4/2087/971580)
difficult to check observationally such a small effect of $e^-$-capture SNe on the velocity distribution.

### 3.2 Spin–velocity alignment in young NSs

The effect of binary progenitors is more interesting for the expected NS spin–velocity alignment. In Fig. 2, we plot the calculated spin–velocity alignment angle $\delta$ for different kick–spin angles $\theta$. The results are shown for young NSs in the model BBS. The spin and velocity vectors appear more aligned for a strong initial kick–spin alignment (i.e. small angles $\theta$).

The effect of binaries can also be illustrated (see Fig. 3) showing the relative contribution of single and binary progenitors to the pulsars with given $v$ and $\delta$. Calculations are made for models SA and BB with $v_p = 300\,\text{km}\,\text{s}^{-1}$, and a fiducial value of the kick–spin alignment of $\theta = 8^\circ$ (the justification is given in Section 4). It is seen that NSs from single progenitors (model SA) are more abundant (i.e. the ratio of single to binary progenitors is more than one) at low velocities $v$ (except for very low values $\lesssim 30\,\text{km}\,\text{s}^{-1}$) and small angles $\delta$. In contrast, pulsars with $v \gtrsim 100\,\text{km}\,\text{s}^{-1}$ and $\delta \gtrsim 15^\circ$–$20^\circ$ are more likely to be born in a binary than from a single star (the single/binary progenitor ratio is smaller than one).

Let us consider more closely the spin–velocity alignment in pulsars originated from different progenitors (Fig. 4). A pulsar can result either from a single massive star or from the primary or secondary component of a massive binary system. In pulsars from single stars, the spin–velocity alignment should reflect the kick–spin correlation during NS formation. In pulsars from binary progenitors, the initial correlation can be different depending on the conditions and history of NS formation. The NS formed after the collapse of the primary component $M_1$ (NS1) can become an isolated radio pulsar ($M_1 \rightarrow NS1 = \text{PSR1 I}$) immediately after the first SN explosion if the binary becomes unbound, or after the second SN explosion ($M_1 \rightarrow NS1 = \text{PSR1 II}$) (filled squares and crosses in Fig. 4, respectively). Pulsars can also result from the collapse of the secondary component $M_2$ when the binary system has already been disrupted by the first SN explosion ($M_2 \rightarrow NS2 = \text{PSR2 I}$) or when the system became unbound after the second SN ($M_2 \rightarrow NS2 = \text{PSR2 II}$). These cases are marked in Fig. 4 with filled circles and triangles, respectively. If the system remained bound after both
explosions, a binary NS is formed; we discussed their coalescences in our previous paper (Postnov & Kuranov 2008). For comparison, open circles in Fig. 4 show the spin–velocity angle distribution for pulsars originated from single progenitors.

Fig. 4 demonstrates that the population of single pulsars originated from binaries is largely dominated by those born after the disruption of the parent binary system by the first SN (PSR1 I and PSR2 I), which constitute roughly ~50 and ~40 per cent of the entire population, respectively.

The effect of the e−-capture SNe, which is taken into account in models BB and BBS, should be mentioned explicitly. PSR1 I in these models are NSs originated from stars with \( M_1 > 11 M_\odot \), i.e. those which did not experience an e−-capture SN. Conditions for an e−-capture SN are such that a system always survives after the first explosion. PSR2 II are mostly NSs from systems where the first explosion was an e−-capture event presumably producing small kicks so that the binary system survives, while the second explosion was due to the usual core collapse event. This happens when the secondary companion significantly increased its mass above \( 11 M_\odot \) due to mass transfer from the primary companion.

Pulsars originated from binaries disrupted after the second SN (PSR1 II and PSR2 II) provide a minor contribution but have, on average, larger spin–velocity alignment angles \( \delta \). Recycled pulsars, which can be spun up by accretion in the binary after the first SN explosion, are among our population PSR1 II and constitute less than a few per cent of all pulsars.

The number of PSR2 II is about 2.5 times larger than that of PSR1 II. This may seem counterintuitive. Both numbers are small, and the difference is just 2.7 per cent of the total number of isolated PSRs. The overabundance of PSR2 II in comparison with PSR1 II is mainly due to the fact that there are binary systems in which the secondary components end up as a NS, but the primary as a black hole (BH). These systems have more changes to remain bound after the first SN explosion (in general, this depends on the mass of a BH formed and the assumed BH kick velocity). Still, such binaries can be disrupted after the second SN explosion thus giving rise to a PSR2 II. In our case, this effect is responsible for 2.3 per cent of the total 2.7 per cent difference. The additional 0.4 per cent comes from another effect. Some of the pulsars formed from the primary companions can already cross the death line in the \( p-p \) diagram by the moment of the second SN explosion. So, after the system becomes unbound only the second (younger) NS can be a radio pulsar, and the older one is a dead pulsar.

We also checked for the possibility of accretion-induced BH formation. The first NS formed in a binary can accrete enough matter to collapse. In our calculations, this effect is found to be negligible.

4 DISCUSSION

It is interesting to compare the calculated spin–velocity angles \( \delta \) in single pulsars with observations assuming different model parameters. Unfortunately, there are only a few precise estimates. In Ng & Romani (2007) and Rankin (2007), the authors present lists of pulsars for which the angle \( \delta \) can be inferred from observations. The cumulative (normalized) distributions of spin–velocity alignment angles (folded around 45° due to the 90° ambiguity in alignment angles measured by radio polarization) in pulsars from these lists are shown in Fig. 5. For several well-studied objects (see Ng & Romani 2007 and references therein), this angle can be determined from a detailed 3D modelling with account of the X-ray data about the pulsar wind nebula shape, etc. For most pulsars, the existing estimates of the spin–velocity angle \( \delta \) are based only on radio observations. In the last case, the angle between the spin axis and its space velocity is derived from measurements of the proper motions of the pulsar on the sky and the polarization angle of radio emission. The angle determined as a difference between the proper motion direction and the pulse polarization angle spans the range from \( \sim -60° \) to \( \sim 100° \) (Johnston et al. 2007; Rankin 2007). However, as we are interested just in the angle between the velocity and rotation axis, irrespective of the velocity direction, this angle should lie between 0° and 90°. In addition, projection effects complicate the interpretation of the data (Johnston et al. 2005). On the other hand, for several well-studied objects, for example Vela (Ng & Romani 2007), it is known that although the difference between the proper motion direction and polarization angle points to the spin axis perpendicular to the velocity, in reality \( \delta \) is close to zero. This is interpreted as being due to the pulsar predominantly emitting radiation, which is polarized perpendicular to the magnetic field lines. So, it is quite common (Johnston et al. 2007; Ng & Romani 2007) to fold data in such a way that the value of the spin–velocity angle lies within the range 0° &lt; \( \delta \) &lt; 45°.

The spin–velocity angle distributions are calculated for different kick–spin angles \( \theta \), different kick velocities and assumptions about the initial binary mass ratio distribution. The comparison is made with both data sets by Ng & Romani (2007) and Rankin (2007). The Kolmogorov–Smirnov (K–S) test was applied to test the null hypothesis that the observed (Fig. 5) and calculated alignment angles are realizations of one distribution. The results are shown in Figs 6–8. The calculated and observed spin–velocity angles \( \delta \) were binned in 23 two-degree intervals to increase the number of bins above 20, as recommended for the K–S test. Since the observational data are folded back to \( \delta < 45° \), the same folding was applied to the calculated alignment angles.

Fig. 6 shows a 3D graph for the K–S test of the model distribution as a function of the fraction of binary progenitors (we mix models SA and BB) and the kick–spin angle \( \theta \). Both panels of Fig. 6 are shown for \( v_p = 300 \text{ km s}^{-1} \) and \( d\delta/dq \sim \epsilon^2 \). The left- and right-hand panels present comparisons with data from Ng & Romani (2007) and from Rankin (2007), respectively. It can be seen that better fits are obtained for a high fraction of binary systems. In particular, in
the case of comparison with the data from Rankin (2007), a small fraction of binary progenitors is disfavoured.

We studied the influence of the fraction of binary progenitors for different kick velocities on the quality of the K–S test. For both samples of observed pulsars (from Ng & Romani and from Rankin) for reasonably high velocities ($v_p > 100$ km s$^{-1}$), the fraction of binary progenitors should be higher than ~50 per cent to produce high quality of the test. For more realistic velocities ($v_p \sim 200$–300 km s$^{-1}$), comparison of our calculations with observational data favours a high fraction of binary progenitors $\gtrsim 70$ per cent, in correspondence with observations of binary frequencies among massive stars (Mason et al. 1998; Gies 2008).

The K–S test for the observed and calculated spin–velocity alignment angles $\delta$ in pulsars as a function of the assumed kick–spin alignment angle $\theta$ and the ratio of binary and single progenitors of the population of isolated NSs. The latter is given as $N(\text{model BB})/(N(\text{model BB})+N(\text{model SA}))$. Calculations are shown for model BBS. The initial binary mass ratio distribution is $f(q) \sim q^2$, and the kick velocity amplitude is equal to 300 km s$^{-1}$. Left-hand panel: comparison with the data from Ng & Romani (2007). Right-hand panel: comparison with the data from Rankin (2007).

Fig. 7 shows the K–S test calculated for model SA (upper panels) and BB (lower panels), as a function of angle $\theta$, for pulsars from Ng & Romani (2007) (to the left) and Rankin (2007) (to the right). Fig. 8 shows the K–S test for models BAS and BBS with different assumptions about the initial mass ratio distribution $f(q)$.

It is seen from Figs 7 and 8 that the K–S test in all cases does not show good correspondence between the observed and calculated pulsar spin–velocity distributions, which may be related to poor statistics of pulsars with known $\delta$. Nevertheless, the K–S maxima are clearly distinguished in all plots, so the K–S test can be used as a guide to assess the relative goodness of the fits.

The K–S test for the observed and calculated spin–velocity alignment angles $\delta$ in pulsars as a function of the assumed kick–spin alignment angle $\theta$. Calculations are shown for the initial binary mass ratio distribution $f(q) \sim q^2$ and models SA and BB. Squares, circles and triangles mark the kick velocity amplitudes 100, 300 and 500 km s$^{-1}$, respectively. Left-hand panels: comparison with the data from Ng & Romani (2007). Right-hand panels: comparison with the data from Rankin (2007).
Figure 8. The K–S test for the observed and calculated spin–velocity alignment angles $\delta$ in pulsars as a function of the assumed kick–spin alignment angle $\theta$. Calculations are shown for the initial binary mass ratio distribution $f(q) \sim q^0$ and $f(q) \sim q^2$ (the upper and lower panels, respectively) and different models (BAS, BBS). Squares, circles and triangles mark the kick velocity amplitudes 100, 300 and 500 km s$^{-1}$, respectively. Left-hand panels: comparison with pulsar data from Ng & Romani (2007). Right-hand panels: comparison with pulsar data from Rankin (2007). It is seen that the form of the initial binary mass ratio distribution and type of kick velocity models (BAS, BBS) have no influence on the results.

For all kick models and initial mass ratio distributions, the data taken from Ng & Romani (2007) are best-fitted by kick velocities confined within the angle $\theta \sim 20^\circ$. In contrast, the comparison with more numerous data by Rankin (2007) favours a narrower natal kick–spin alignment with $\theta \sim 5^\circ$–$10^\circ$. This explains our choice of the fiducial value $\theta = 8^\circ$ we used in Figs 3 and 4. Note also that data by Rankin (2007) can hardly be fitted by single progenitors only (model SA, the upper-right panel in Fig. 7).

Fig. 8 clearly shows that the results only slightly depend on the chosen kick model and the kick velocity amplitude, and are virtually independent of the assumed initial binary mass ratio distribution $f(q)$.

It may seem that the actual shape of the kick velocity distribution can be an important parameter. In our study, we restrict ourselves to considering only the simplest case of a single-peak Maxwellian distribution for most of the NSs, in reasonable agreement with observations. As our kick model B assumes the formation of a certain fraction of low-kick NSs and, hence, low-velocity pulsars, the obtained insignificant dependence of the calculated spin–velocity alignment on kick models (at least with the current pulsar data at
hand) suggests that the true shape of the kick is not so important. However, it does matter for the estimation of the relative fraction of single and binary pulsar progenitors at given $\delta$ and $v$ (Fig. 3). For example, if the true kicks can take values close to zero even for single progenitors, it would be hard to distinguish binary and single progenitors from such an analysis.

5 CONCLUSIONS

In the present paper, we considered the role of binary progenitors of neutron stars in the apparent distribution of space velocities and spin–velocity alignment of young pulsars. We used a Monte Carlo synthesis of pulsar population from single and binary stars under different assumptions about the NS natal kick model (form, amplitude and possible reduction of the kick in binary progenitors with masses from the range 8–11 $M_\odot$) and initial binary mass ratio distributions. We compared the calculated spin–velocity alignment distributions with observational data obtained from radio polarization measurements. We arrived at the following conclusions.

(1) The observed space velocity of pulsars is mostly shaped by the assumed natal kick velocity form and amplitude (Fig. 1). The effect of binary progenitors is negligible.

(2) The possible kick–spin alignment during the formation of a NS strongly affects the spin–velocity correlation in pulsars. For the kick model considered, single progenitors are more probable for pulsars with space velocities $>50 \text{ km s}^{-1}$ and tight spin–velocity alignment ($<10^\circ$) (Fig. 3). Binary progenitors are favoured for pulsars with $\delta \gtrsim 15^\circ$ and $v \gtrsim 100 \text{ km s}^{-1}$, and for low-velocity pulsars ($<30 \text{ km s}^{-1}$) for all values of $\delta$.

(3) The comparison with current measurements of pulsar spin–velocity angles (Ng & Romani 2007; Rankin 2007) does not allow us to distinguish between different kick models -- the agreement between the calculated spin–velocity alignment and the observed distributions is not very good (Figs 7 and 8). Nevertheless, the assumption of natal kick–spin alignment during NS formation appears to be more important than the kick velocity distribution model.

Single progenitors only (model SA, Fig. 8) do not fit well data by Rankin (2007) and provide a worse fit for the sample of pulsars studied by Ng & Romani (2007) than binary progenitors. Models with equal numbers of single and binary progenitors of isolated young NSs (models BAS, BBS, Fig. 7) equally well fit observations irrespective of the assumed form of the initial binary mass ratio distribution $f(M)$. Binary progenitors only (model BB, Fig. 7) can equally well fit both data by Ng & Romani (2007) and Rankin (2007) for the kick–spin velocity angle $\theta \sim 5^\circ$–$20^\circ$. We conclude that only single progenitors of radio pulsars (model SA) are unlikely for high mean kick velocities $v_p \sim 300 \text{ km s}^{-1}$.

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