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CONSTRAINTS ON NATAL PULSAR KICKS FROM ECCENTRIC BINARY PULSARS

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ABSTRACT

We investigate the expected space velocities and misalignment angles of the eccentric binary pulsars for a range of possible progenitor systems and natal kick models. In particular, the effect of the orbital separation at the instant of supernova is discussed. The results of our simulations, combined with recent proper-motion and misalignment angle measurements, lead us to conclude that, although the known systems generally provide evidence for asymmetric supernovae, none of the proposed natal kick velocity distributions are adequate. Instead, we find that while kicks are required to explain the space velocities of J0045−7319 and B1259−63, a slow kick velocity distribution with $\sigma = 0$ km s^{-1} and $\mu = 50$ km s^{-1} predicts space velocities that demonstrate the best agreement with observation. The expected misalignment angle distributions for B1534+12, J0045−7319, and B1259−63 favor larger kicks but do not preclude a slow kick velocity distribution. Such a model is, however, inconsistent with the large kicks usually invoked to explain the velocities of single pulsars. We discuss possible means to reconcile the space velocities of eccentric binary pulsars and the velocity distribution of the pulsar population. These include constraining the progenitor systems of binary pulsars to preclude tight post–common-envelope systems and erroneous pulsar velocity measurements due to an inaccurate distance model.

Subject headings: binaries: close — pulsars: general — stars: kinematics

1. INTRODUCTION

The inability of traditional evolutionary models to explain both the high space velocities of isolated pulsars (Lyne 1981) and the relative paucity of binary radio pulsars (only ∼1% of the observed high-field population) prompted Shklovskii (1970) to propose that pulsars receive a natal "kick" during asymmetric supernovae. Since then, there has been considerable discussion about the possible magnitude of these kicks and the effects that they would have on the observed radio pulsar population. Iben & Tutokov (1996) is perhaps the only recent study questioning the validity of the kick hypothesis, arguing that the observed velocity distribution of pulsars can be accounted for by binary systems recoiling from the sudden mass loss during a supernova. Their findings against the existence of kicks, however, have been rejected by both van den Heuvel & van Paradijs (1997) and Lorimer, Bailes, & Harrison (1997). The observation of geodetic precession in B1913+16 (Weisberg, Romani, & Taylor 1989) and the misalignment of the orbital angular momentum and spin axes in the main-sequence–neutron star (hereafter MS-NS) systems, J0045−7319 and B1259−63 (Kaspi et al. 1996; Wex et al. 1998), further refute Iben & Tutokov's arguments. Notable studies in support of the kick hypothesis include Dewey & Cordes (1987), Bailes (1989), Lyne & Lorimer (1994), Brandt & Podsiadlowksi (1995), Kaspi et al. (1996), and Fryer & Kalogera (1997). The natal kick velocity distributions that these authors have proposed, however, are quite diverse. In part, this reflects revised estimates for the mean birth velocity of pulsars—from 100 km s^{-1} (Gunn & Ostriker 1970) to 450 km s^{-1} (Lyne & Lorimer 1994, proper-motion data) and even 990 km s^{-1} (Frail, Goss, & Whiteoak 1994, supernova remnant associations). Currently, the favored mean kick velocity is ∼200 km s^{-1} (Tauris & Bailes 1996; Hansen & Phinney 1997; Kalogera, Kolb, & King 1998).

For this paper, we investigated the effects of various kick velocity distributions on the expected space velocities of the eccentric binary pulsars B1913+16, B1534+12, J1518+4904, and B2303+46. On evolutionary grounds, the lack of an optical companion to these pulsars is customarily regarded as evidence that these binaries are double neutron star systems; we shall hereafter refer to them as DNS systems. (There is no observational test to disqualify a white dwarf companion for B1913+16. The system's high eccentricity and evolutionary history, however, demand that the pulsar's companion was formed in a supernova after the pulsar spin-up phase [Srinivasan & van den Heuvel 1982]). We further investigate the effect of the various kick velocity distributions on the expected misalignment angles of J0045−7319 and B1259−63, two binary pulsars with massive, optical companions. The expected misalignment angle distribution of B1534+12 is also studied. We expect that natal kicks will, in general, decrease the number of surviving binaries (Hills 1983) but increase their space velocities (Cordes & Wasserman 1984). Furthermore, we expect that systems that receive large natal kicks are more likely to display significant misalignment of their orbital angular momentum and spin axes (Brandt & Podsiadlowksi 1995). The two latter effects should be particularly pronounced in highly eccentric, short orbital period systems (e.g., B1913+16) that appear to have only just survived their second supernova.

As suggested by Wijers, van Paradijs, & van den Heuvel (1992), binary pulsars can be regarded as "well-preserved fossils" of their progenitor systems, as long as the spin-down age is much less than the time required for gravitational radiation losses to change the postsupernova orbit. This is a reasonable assumption for all our systems, allowing us to idealize the effect of the supernova and natal kick on the progenitor system into a problem of Newtonian point-mass mechanics. We can then produce expected space

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velocity and misalignment angle distributions for each eccentric binary by integrating over a range of possible progenitor systems and kick velocity distributions. In § 2, we present a detailed description of our method for doing this and discuss further simplifying assumptions used in our calculations. The resultant space velocity and misalignment angle distributions are described in § 3, where we also examine the viability of various natal kick velocity distributions. We find that the measured space velocities of B1913+16 ($\sim 100 \pm 41$ km s^{-1}; Taylor & Weisberg 1989), B1534+12 ($\sim 136 \pm 25$ km s^{-1}; Stairs et al. 1998), and B1518+4904 ($\sim 27 \pm 8$ km s^{-1}; Nice, Taylor, & Sayer 1999) are consistently low compared with the velocities predicted by our distributions. Constraints on the presupernova orbital separation of the progenitor binary have a relatively small impact on these results. The expected space velocity distributions of the MS-NS systems do, however, seem to vindicate the natal kick hypothesis. In § 3 we discuss the misalignment angle of B1534+12, which determines the maximum observable rate of the geodetic precession of the binary (Cordes & Wasserman 1984). Our conclusions are presented in § 4.

2. METHOD

As a nonrelativistic binary undergoes minimal orbital evolution, we can invoke conservation laws to constrain the presupernova parameters of the system from a knowledge of its current orbital parameters (see Sutantyo 1978; Dewey & Cordes 1987 and Wijers et al. 1992). The unknown parameters of the progenitor binary are the mass of the exploding helium star immediately prior to the supernova, $M_{\rm He}$, and the presupernova orbital separation, a_i. The magnitude and direction of the natal kick imparted to the nascent neutron star are also unknown. A possible progenitor of one of our eccentric binary pulsars, however, must have postsupernova Keplerian parameters identical to those observed for the system; Table 1 lists the measured binary periods and eccentricities of each of the pulsars in our study. These Keplerian parameters are fixed by the binary's orbital angular momentum and the relative velocities of the two component stars, which also constrain the natal kick to lie on one of two concentric " circles " in velocity space (see Fig. 1).

For our simulations, we integrate the Newtonian equations governing the space velocity and misalignment angle of a binary system over plausible values for $M_{\rm He}$, a_i, and $v_{\rm kick}$ in order to produce expected space velocity and misalignment angle distributions for each of the eccentric binary pulsars. Having weighted our calculations for a proposed natal kick model, we compare the resultant distributions with the measured proper motions and misalignment angles of the known eccentric binary pulsars. Our intention is to constrain the form of the natal kick velocity distribution.

TABLE 1

THE CURRENT ORBITAL PERIODS AND ECCENTRICITIES OF THE ECCENTRIC BINARY PULSARS

Pulsar	Orbital Period (days)	Eccentricity
B1913+16........	0.322997	0.61713
J1518+4904......	8.6340047	0.24948481
B1534+12........	0.420737301	0.273679405
B2303+46........	12.33954	0.65836
J0045−7319......	51.16945	0.80794901
B1259−63........	1236.72359	0.8699310

NOTE.—From the revised catalog of Taylor, Manchester, & Lyne 1993.

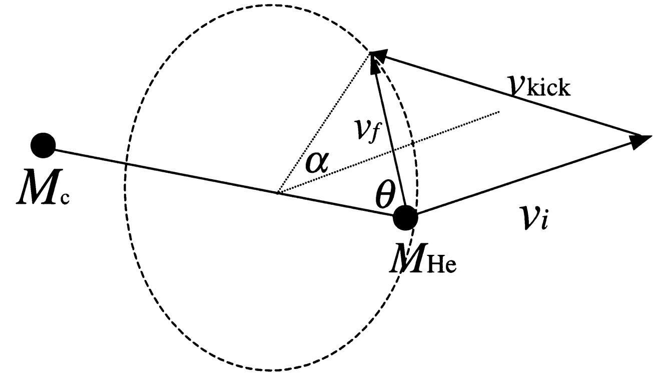

FIG. 1.—Binary space and supernova kick geometry. The random kick, described by its magnitude and the angles θ and α, propels the nascent neutron star onto one of two concentric circles in velocity space. For clarity, only one circle is illustrated here.

Fortunately, it is not difficult to establish reasonable constraints on a_i. The postsupernova orbit of the binary must contain the distance between the two stars at the instant of supernova, allowing us to restrict a_i to lie in the interval $a_f(1 - e) < a_i < a_f(1 + e)$, where e is the orbital eccentricity. (Throughout this paper, the subscript f denotes a postsupernova parameter, while i indicates a presupernova one). We assume that supernovae occur instantaneously, that the ejected matter from the exploding star does not interfere with the companion, and that the binary orbit is circular prior to the supernova. These assumptions are quite common and are discussed in Fryxell & Arnett (1981). We further assume that the mass of a neutron star, $M_{\rm ns}$, is 1.4 $M_\odot$ (Thorsett 1996) and that the mass of the companion star in the MS-NS binaries is 10 $M_\odot$ (Johnston et al. 1994; Bell et al. 1995). The mass of the exploding helium star is constrained in our calculations to lie between 2.2 and 3.6 $M_\odot$ (Woosley, Langer, & Weaver 1995). Progenitor systems for which the presupernova orbital separation is less than the radius of the exploding helium star are rejected. We use the mass-radius relations that appear in Kalogera & Webbink (1996) to calculate evolved helium star radii. As noted by Burrows & Woosley (1986), moreover, the minimum Roche lobe radius that avoids rapid core coalescence in DNS binaries is $\sim 1\ R_\odot$. We use Eggleton's equation for the Roche lobe limit, therefore, to restrict the allowed minimum presupernova orbital separation to $a_i > 2.39\ R_\odot$. This final constraint is only relevant for the close orbit eccentric binary pulsar B1913+16.

The velocity of the random kick that propels the system into its final orbit is fixed by the difference between the relative orbital velocity of the two stars and the orbital angular momentum of the binary. It is described not only by its magnitude (which we weight according to a proposed kick velocity model) but also by two angles, α and θ (illustrated in Fig. 1). The angle θ is between the neutron star's postsupernova velocity and a line joining the two stars at the instant of the explosion. On the other hand, α is the angle between the original orbital plane and the new one. Since the spin axis of the pulsar and the angular momentum axis of the binary will have been parallel prior to the supernova, the misalignment angle of the post-supernova binary is also α. The equation

$$\sin\theta = \left[\frac{a}{R}(1-e^2)\frac{1}{2-(R/a)}\right]^{1/2} \quad (1)$$

(Bailes 1988) determines the limits of θ, while α is allowed to vary between 0 and π radians.

In our calculations, every space velocity and misalignment angle is weighted for the magnitude of the kick that formed the binary (according to the proposed natal kick model) and for the presupernova orbital separation. Overall, five kick velocity models were tested. These comprised two broad Gaussian distributions, one with a mean $\mu \sim 450$ km s^{-1} and a standard deviation $\sigma \sim 150$ km s^{-1} (model A), the other with $\mu \sim 0$ km s^{-1} and $\sigma \sim 150$ km s^{-1} (model B), a narrow Gaussian with $\mu \sim 0$ km s^{-1} and $\sigma \sim 50$ km s^{-1} (model C), and a Maxwellian with $\sigma_v \sim 190$ km s^{-1} (model D; Hansen & Phinney 1997). A model devised by Lipunov, Postnov, & Prokhorov (1997), which reproduces the pulsar birth velocity distribution of Lyne & Lorimer (1994), was also tested (model E). For comparison, we also calculate the expected space velocity of each eccentric binary pulsar if it had received no natal kick. In this case, the current orbital eccentricity is a direct measure of the mass lost in the supernova. Because the presupernova orbital separation is preserved as the periastron distance of the new orbit, we can use simple Newtonian equations and conservation laws to determine the final relative orbital velocity and expected space velocity of the binary.

Various studies have remarked upon the sensitivity of space velocities to the presupernova orbital separation of the binary (Fryer & Kalogera 1997; Brandt & Podsiadlowski 1995). Constraints on a_i are difficult to justify, however, except perhaps in hindsight. In order to investigate this more fully, every space velocity and misalignment angle distribution is weighted according to the separation of the system's progenitor binary. Four general presupernova orbital separation distributions were applied to our calculations: a model for which $\Gamma(a_i) \propto a^{-1}$, another for which $\Gamma(a_i) \propto a_i$, and two linear distributions that weight the calculations linearly for and against large presupernova orbital separations. By doing so, we hope to better our understanding of the orbital separations of eccentric binary pulsar progenitors. Expected space velocities and misalignment angle distributions that are not weighted in any way for a_i were also produced for each of the eccentric binary pulsars.

3. RESULTS AND DISCUSSION

3.1. *Space Velocities of DNS Systems*

Examining our results for the DNS systems, it is striking how insensitive they are to the various applied natal kick and presupernova orbital separation distributions (see Fig. 2). As we would expect, the close orbit systems allow for the greatest possible space velocities: the small orbital separation producing higher initial and final relative velocities and favoring faster kicks. Similarly, the presupernova orbital separation model that is linearly weighted against large a_i favors higher space velocities, shifting the distribution peak by up to $\sim$15%. Restricting a_i to be greater than 2.39 $R_\odot$, on the other hand, removes the high-velocity tail from B1913+16's expected space velocity distribution, shifting the maximum possible space velocity from $\sim$700 to $\sim$430 km s^{-1}. The wider orbit systems, B2303+46 and J1518+4904, have maximum possible and most probable space velocities that are considerably lower than their close orbit cousins—only $\sim$240/70 km s^{-1} and $\sim$160/115 km s^{-1}, respectively, compared with $\sim$430/260 km s^{-1} (B1913+16) and $\sim$460/300 km s^{-1} (B1534+12). Although the correlation between the faster kick models and higher expected space velocities seems clear, we note that the variation in most probable space velocity for each DNS system is almost negligible for different presupernova orbital separation distributions (besides the aforementioned exception, which weights against large a_i) and for the kick models A, B, D, and E. Model D, however, does seem to increase the proportion of high-velocity systems slightly. Only the expected space velocity distributions produced by kick model C, a narrow Gaussian with $\sigma = 50$ and $\mu = 0$, are markedly different. For this model, the proportion of low-velocity systems is considerably increased, and the most probable space velocity is reduced: $\sim$150 km s^{-1} (B1913+16), $\sim$80 km s^{-1} (B1534+12), $\sim$25 km s^{-1} (J1518+4904), and $\sim$60 km s^{-1} (B2303+46). Varying the preferred presupernova orbital separation distribution does not have a significant impact on these results.

Although we note that velocities inferred from proper-motion measurements are extremely sensitive to the assumed distance, it is evident that most of our kick velocity models considerably overestimate the proper motions of B1913+16, B1534+12, and B1518+4904 (see Table 2). Kick model C predicts space velocities for the DNS systems that display the best correlation with proper-motion observations, but fast natal kicks are required to explain the observed velocity distribution of the single pulsar population (Lyne & Lorimer 1994). Although the sample size of eccentric binary pulsars is small, it is clear that an explanation of their low space velocities is required.

Spruit & Phinney (1998) have recently suggested that the kick imparted to a nascent neutron star may not be a single event, but rather several random momentum impulses acting on the neutron star during its formation. They argue that if the duration of each momentum impulse was comparable to the orbital period of the binary, then rotational averaging would considerably reduce the contribution to the components of kick velocity perpendicular to the rotation axis. Because of this effect, Spruit & Phinney estimate that short-period systems should have mean birth velocities $\sim 1/\sqrt{3}$ lower than longer period systems. This suggestion is innovative, since the close orbit eccentric binary pulsars B1913+16 and B1534+12 require small kicks to be consistent with their low measured space velocities.

Fryer & Kalogera's (1997) study of the orbital dynamics of DNS systems provides another plausible explanation for their apparently low space velocities. Crucially, they argue that possible close orbit progenitors of DNS systems could not survive the common-envelope phase of binary evolution. By increasing the lower limit on stellar separation at supernova for their progenitor systems, the probability of very high space velocities is reduced, even for a high-velocity kick distribution. Indeed, Fryer & Kalogera derive a lower limit of 200 km s^{-1} on the natal kick received by each of the close orbit binaries (B1913+16 and B1534+12). Their study predicts minimum space velocities of 200 and 225 km s^{-1} for B1913+16 and B1534+12, respectively,

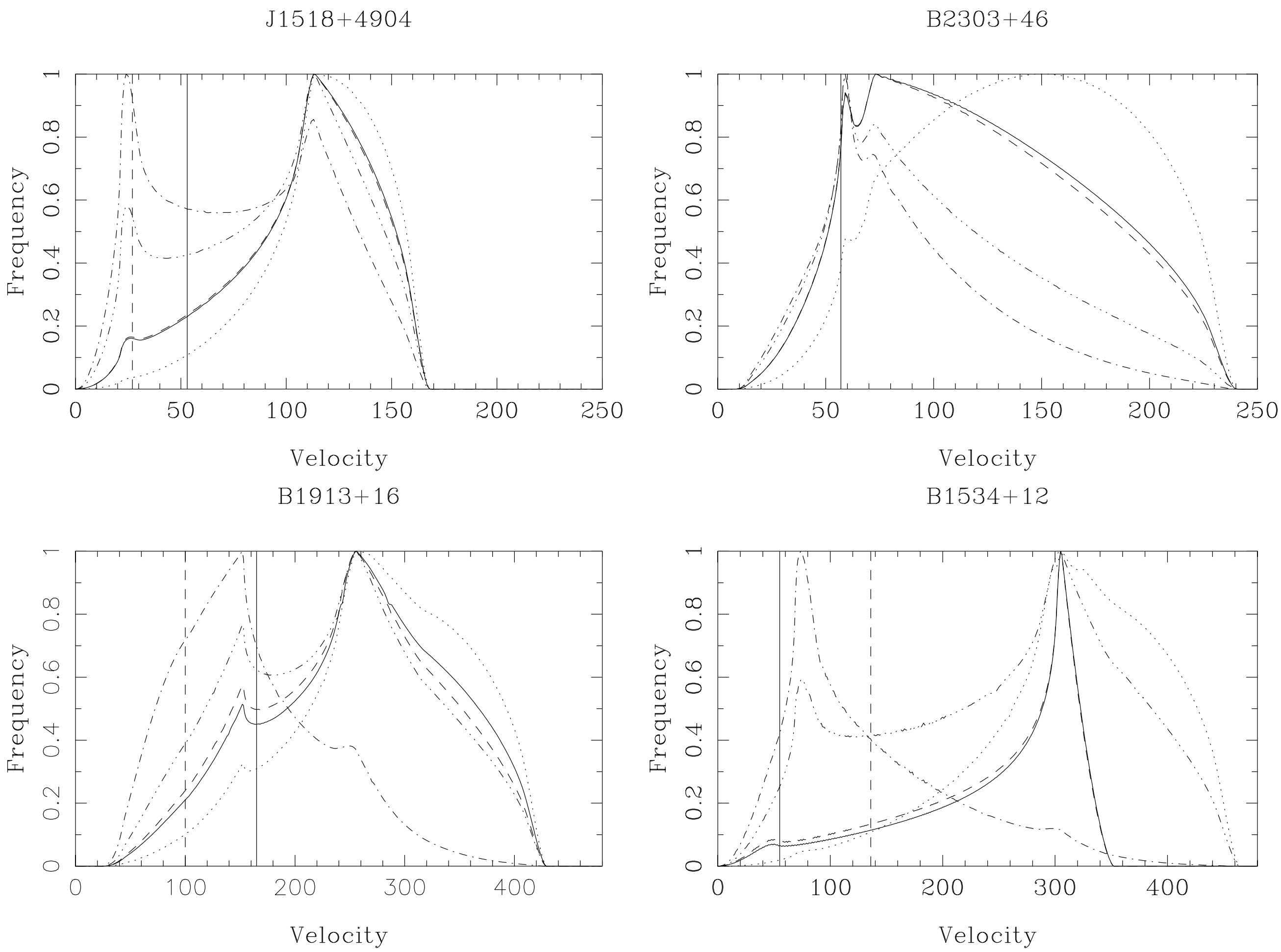

FIG. 2.—Space velocity distributions of DNS systems, B1913+16, B1534+12, B2303+46, and J1518+4904. Shown is the distribution weighted by the kick model A (*solid curve*), model B (*dashed curve*), model C (*triple-dot–dashed curve*), model D (*dotted curve*), and model E (*dash-dotted curve*). The vertical lines represent (1) the space velocity of the system if it had received no natal kick (*solid line*) and (2) the space velocity of the system inferred from proper-motion measurements (*dashed line*) if it is known. The distributions shown are not weighted for the orbital separation of their progenitor.

and 50 km s^{-1} for the wider DNS binaries. Given the sensitivity of these values to distance measurements and the small number of systems involved, the space velocities determined by Fryer & Kalogera are reasonably consistent with the measured proper motions of the DNS binaries (see Fig. 2).

Two further factors may partially account for the apparently low space velocities of the DNS binaries: selection

TABLE 2

MEASURED PROPER MOTIONS OF THE ECCENTRIC BINARY PULSARS

Pulsar	Distance (kpc)	Measured Proper Motion (mas yr^{-1})	Proper Motion (mas yr^{-1}) 1	2
B1913+16	7.1	3.0	7.7	4.4
J1518+4904	0.70	8.0	34.6	7.5
B1534+12	0.68	25.5	93.0	21.7
B1534+12*	1.2	25.5	52.7	12.3
B2303+46	4.34	...	7.3	2.9
J0045−7319	57.0	...	0.1	0.05
B1259−63	4.6	...	0.6	0.2
B1259−63*	2.3	...	1.2	0.5

NOTE.—The expected proper motions of the studied systems for (1) a Gaussian natal kick distribution with $\mu = 450$ km s^{-1} and $\sigma = 150$ km s^{-1} and (2) a Gaussian natal kick distribution with $\mu = 0$ km s^{-1} and $\sigma = 50$ km s^{-1} are also listed. Distances are derived from the Taylor & Cordes 1993 distance model for all the binaries save B1534+12*, for which we used a distance of 1.2 kpc (Stairs et al. 1998), and B1259−63*, for which we used 2.3 kpc (Johnston et al. 1992).

effects and the motion of the systems in the galaxy. On average, eccentric binary pulsars will be decelerated in the Galactic potential, and very fast systems will escape. Moreover, studies of the kinematic properties of millisecond pulsars in low-mass X-ray binaries show that a volume-restricted population has space velocities that are significantly smaller on average than the whole population (Ramachandran & Bhattacharya 1997). We should not be surprised, therefore, that the space velocities of observed DNS systems will be slightly slower than we might initially expect.

Perhaps the simplest and most convincing explanation for the disparity between the expected and measured space velocities of the DNS binaries, however, is an inaccurate distance model. Previous kick velocity and pulsar birth velocity distributions have been proposed primarily on the basis of proper-motion measurements for nearby single pulsars. Converting proper motions to transverse velocities, however, is highly sensitive to the assumed distance. While the distance model of Taylor & Cordes (1993) predicts the distance to nearby pulsars quite successfully, independent measurements for the more distant pulsars are often inconsistent with the Taylor & Cordes model by up to a factor of 2 (see, for example, Toscano et al. 1998; Sandhu et al. 1997; Bell & Bailes 1996). Stairs et al. (1998) have determined the true distance to B1534+12 to be 1.2 kpc (compared with 0.7 kpc predicted by the Taylor & Cordes distance model), while Johnston et al. (1992) argue that the true distance to B1259−63 is only 2.3 kpc, not 4.6 kpc. If the galactic distribution of free electrons is not as well understood as the Taylor & Cordes distance model assumes, then the pulsar birth velocity distribution (and, correlatively, the natal kick velocity distribution) could be erroneously biased toward high velocities. Although there are relatively few pulsars with independent distance measurements at this time, we believe that a revised distance model may be influential in resolving the discrepancy between the measured velocities of the DNS binaries and the estimated birth velocity distribution of single pulsars.

In summary, we find that the DNS systems provide only minimal support for the natal kick hypothesis, their "no-kick" space velocities often making a better approximation to the velocities inferred from proper-motion measurements than those predicted by our distributions with underlying kick models. We do note, however, that there are many uncertainties involved in inferring space velocities from proper-motion data and that we are still dealing with a very small number of systems.

3.2. *Space Velocities of MS-NS Systems*

Until the discovery of B1259−63 in 1992 (Johnston et al. 1992), there had been no observation of a radio pulsar in orbit around a main-sequence companion. B1259−63's discovery was quickly followed by that of J0045−7319 (Kaspi et al 1994), and both systems have since provided a valuable insight into the evolution of binary and single pulsars. As Figure 3 illustrates, each of our kick models produces remarkably similar space velocity distributions for the MS-NS binaries, although the position of the peak varies by up to ~ 30 km s^{-1} for J0045−7319 and ~ 15 km s^{-1} for B1259−63. The shape of the resultant space velocity distributions, however, is considerably less sensitive to the variation in the applied kick velocity model than for the DNS systems. We attribute this to the high companion mass and wider range of allowed a_i values for the MS-NS binaries. Variations in the applied presupernova orbital distribution also seem to have little effect on our results. As expected, our calculations predict that J0045−7319 should be the faster of the two binaries, with an expected space velocity of ~ 30 km s^{-1}, while the wide orbit system B1259−63 should be traveling with $v_{sp} \sim 10$ km s^{-1}. Significantly, however, the expected space velocities for these systems, if they receive no natal kick, is almost 6 times greater than the peak of the velocity distributions produced by our kick models: ~ 155 km s^{-1} for J0045−7319 and ~ 70 km s^{-1} for B1259−63. J0045−7319 is situated in the Small Magellanic Cloud and has a heliocentric radial velocity that is comparable to that of other stars and gas in the same region (Bell et al. 1995). We can reasonably expect that a "no-kick" space velocity of 150 km s^{-1} would have a significant radial component, for which Bell et al. found no

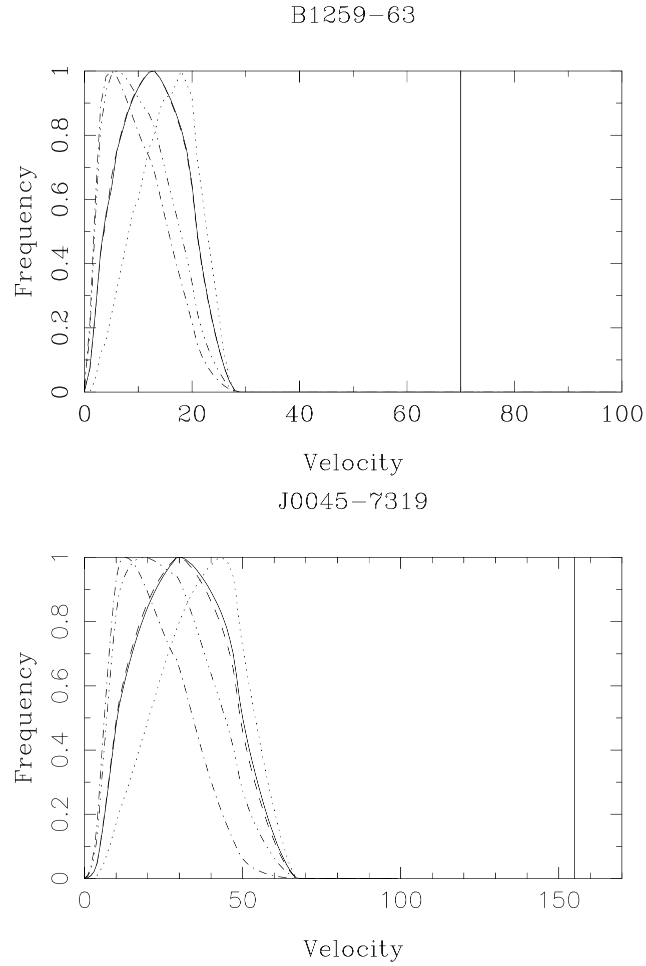

FIG. 3.—Space velocity distributions of MS-NS systems, B1259−63 and J0045−7319. Shown is the distribution weighted by the kick model A (*solid curve*), model B (*dashed curve*), model C (*triple-dot–dashed curve*), model D (*dotted curve*), and model E (*dash-dotted curve*). The solid vertical line represents the space velocity of the system if it had received no natal kick. Note that this lies beyond the high-velocity tail of the space velocity distribution for both J0045−7319 and B1259−63, since the mass of the exploding helium star in this case lies outside the integration limits used to produce the distributions. Extending these limits to 12 $M_\odot$, however, does not significantly alter the shape of the distribution or the position of its peak. The distributions shown are not weighted for the orbital separation of their progenitor.

evidence. Similarly, a space velocity of 70 km s^{-1} would be discernible in archival optical plates of B1259−63's companion, SS 2883, a study of which should provide decisive evidence in the argument about natal kicks.

3.3. *Misalignment Angles of MS-NS Systems*

The misalignment of the angular momentum and pulsar spin axes of a binary system lends great support to the natal kick hypothesis, since an asymmetric supernova seems to be the only reasonable mechanism by which these axes could become skewed. Tidal interactions and mass exchange ensure that the orbital angular momentum vector and the helium star's spin axis should be aligned prior to the supernova, and an evolutionary scenario that favors symmetric supernovae cannot seem to account for any subsequent misalignment. The proponents of the natal kick hypothesis were therefore encouraged when a misalignment angle was measured for J0045−7319 (25°–41°; Kaspi et al 1996) and inferred for B1259−63 (>55°; Wex et al. 1998). The misalignment angle distributions produced from our calculations for the two MS-NS systems are illustrated in Figure 4.

Clearly, these results are more sensitive to the applied kick velocity model than the space velocity distributions for either the MS-NS or DNS binaries. Although the misalignment angle distributions produced by each of the kick velocity models are relatively uniform (which we expect, since the allowed range of values for a_i for both B1259−63 and J0045−7319 is large), they are nevertheless quite distinct. Hansen & Phinney's (1997) kick distribution consistently favors large misalignment angles, for example, while a slow, narrow Gaussian strongly weights the angular distributions toward minimal misalignment. This is particularly evident in the case of B1259−63, where the results for model C do not even favor a retrograde orbit, i.e., one in which the pulsar is spinning in the opposite direction to which it is traveling around its companion (a retrograde orbit is indicated in our calculations by $\alpha > 90°$). Presupernova orbital separations that weight against large values of a_i favor smaller misalignment angles, but the effect does not seem particularly significant. Although it is evident that the misalignment angle distributions produced from the faster kick models are more consistent with the results of Kaspi et al. (1996) and Wex et al. (1998), each kick model still predicts the measured or inferred misalignment angles of J0045−7319 and B1259−63 with a relative frequency of greater than 0.3. Despite the unique form of each of the misalignment angle distributions, therefore, they cannot reasonably be used to constrain the kick velocity model.

3.4. *Misalignment Angle of B1534+12*

Although the DNS system B1534+12 does not reside in the extreme relativistic regime of B1913+16, it is nonetheless a valuable gravitational laboratory in which to observe general relativistic effects. Of considerable interest is geodetic precession, a phenomenon analogous to spin-orbit coupling in atoms. If the angular momentum axis of the binary system is misaligned with the pulsar's spin axis, the spin axis should precess on a timescale of several hundred years, changing both the orientation of the emission cone and the observed pulse shape. Geodetic precession has been studied at some length in relation to B1913+16 (Esposito & Harrison 1974; Cordes & Wasserman 1984; Bailes 1988), although it was not until 1989 that there was observational confirmation of the binary exhibiting this effect (Weisberg et al. 1989). Nevertheless, as early as 1975, the formula for the "characteristic" precession rate, Ω_p, had been derived:

$$\Omega_p = \frac{3\pi G M_c[1 + M_{\rm ns}/3(M_{\rm ns} + M_x)]}{a(1 - e^2)c^2 P_{\rm orb}}\ , \tag{2}$$

where c is the velocity of light and $P_{\rm orb}$ is the orbital period of the binary (Barker & O'Connell 1975; Hari Dass & Radhakrishnan 1975). In order to translate Ω_p into an observable quantity, however, we must also take into consideration the orientation of the pulse beam with respect to the observer and the misalignment of the orbital angular momentum and the pulsar's spin axes. Cordes & Wasserman (1984) find that

$$\Delta\phi = \Omega_p P_{\rm orb} \cos \eta \sin \alpha\ , \tag{3}$$

where ϕ is the angle between the magnetic axis of the pulsar and the observer's line of sight across the pulsar beam, α is the misalignment angle, and η is defined by

$$\sin \alpha \cos \eta = \frac{\hat{\boldsymbol{n}} \cdot (\hat{\boldsymbol{S}} \times \hat{\boldsymbol{J}})}{[1 - (\hat{\boldsymbol{n}} \cdot \hat{\boldsymbol{S}})^2]^{1/2}}\ . \tag{4}$$

In this equation, $\hat{\boldsymbol{S}}$ is the unit vector parallel to the pulsar's spin vector, $\hat{\boldsymbol{J}}$ is the unit vector parallel to the orbital angular momentum vector, and $\hat{\boldsymbol{n}}$ is the unit vector pointing in the direction of the observer from the pulsar. Change in the pulse shape data is then best related to the quantity $\Delta\phi$.

For B1534+12, the characteristic precession rate is 0°.527 yr^{-1}, determined from the values for orbital period and eccentricity listed in Table 1 and the mass of the system inferred by Stairs et al. (1998). If $\cos \eta = 1$, we obtain the maximum observable rate of geodetic precession by substituting our expected misalignment angle and B1534+12's orbital period and characteristic precession rate into equation (3). The misalignment angle distributions produced from our calculations are quite sensitive to the kick velocity distribution that we apply: model A suggests $\alpha \sim 45°$, corresponding to a maximum observable precession rate of ∼0°.373 yr^{-1}, while model C predicts that there should be no significant misalignment of the orbital angular momentum and pulsar spin axes and hence no observable geodetic precession. Arzoumanian (1995), however, has published evidence for geodetic precession of B1534+12 based on only ∼900 days of timing data.

We are thus faced with the unenviable task of reconciling a relatively low space velocity and significant inferred misalignment angle for the system, a situation that simultaneously suggests both a small and large natal kick! Under normal circumstances, it is unlikely for a binary to receive a high-velocity "retrograde" kick that propels the system into a closer orbit without greatly increasing its space velocity. If we eliminate close orbit progenitors completely, however, then the relative probability of such a scenario occurring is considerably increased (Fryer & Kalogera 1997). This is because the crucial quantity that determines the misalignment angle is the not the kick velocity itself but the relative kick velocity (i.e., kick velocity divided by orbital velocity). If we could find evidence for wide initial orbital separations, then strong relative kick velocities (and hence large misalignments) but low absolute space velocities become more likely. Unfortunately, however, the space

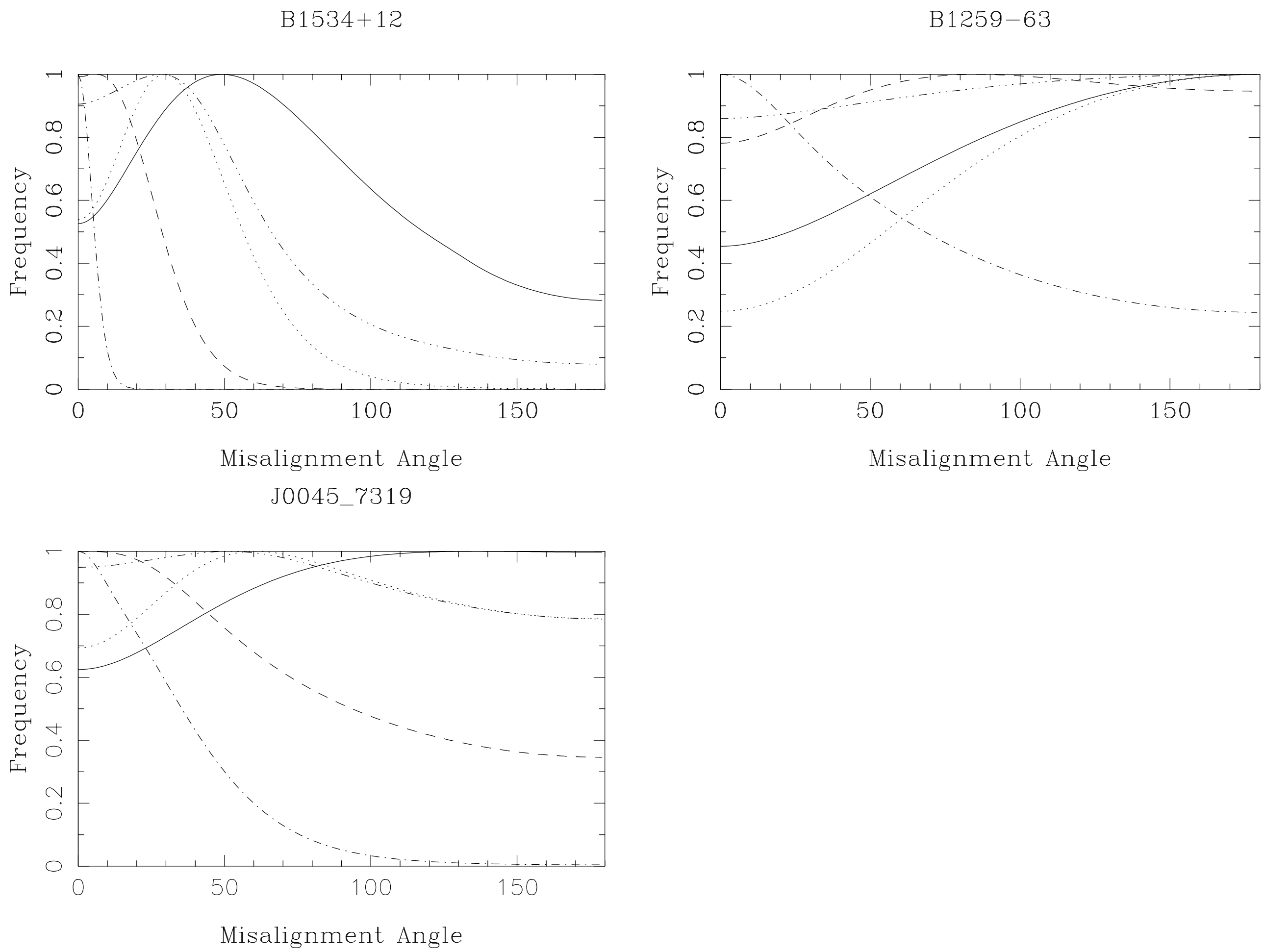

FIG. 4.—Misalignment angle distributions of B1259−63, J0045−7319, and B1534+12. Shown is the distribution weighted by the kick model A (*solid curve*), model B (*dashed curve*), model C (*triple-dot–dashed curve*), model D (*dotted curve*), and model E (*dash-dotted curve*). The distributions shown are not weighted for the orbital separation of their progenitor.

velocity distributions produced by our simulations do not seem overly sensitive to the various a_i models. In particular, the space velocities that have been weighted for large a_i values demonstrate no better correlation with the measured proper motions of B1913+16, B1534+12, and J1518+4904 than space velocities predicted by any of our other presupernova orbital separation distributions. These reservations notwithstanding, we propose a wide initial separation and large relative kick as the evolutionary history for B1534+12. Although it may seem somewhat speculative, we believe that it best explains current observations of the system's proper motion (Stairs et al. 1998) and changes in the pulse shape data at 1400 MHz (Arzoumanian 1995).

4. CONCLUSIONS

We have studied the effects of natal kicks on the expected space velocities of B1913+16, B1534+12, J1518+4904, B2303+46, J0045−7319, and B1259−63 and on the misalignment angles of J0045−7319, B1259−63, and B1534+12. Although our space velocity distributions provide general support for the natal kick hypothesis, we find that none of the currently favored kick models are adequate, since they all predict much higher space velocities for B1913+16, B1534+12, and J1518+4904 than have been observed. Rather, the measured space velocities of the eccentric binary pulsars provide support for a lower natal kick velocity distribution. Restrictions on the orbital separation of the two component stars immediately prior to the supernova may seem likely for evolutionary reasons, but there is no evidence that the known eccentric binary pulsars were formed from wide progenitor systems. We believe that the best explanation for the discrepancy between the expected and measured space velocities of the DNS binaries may be erroneous pulsar velocity measurements from an inaccurate distance model. Alternatively, Spruit & Phinney's (1998) radical mechanism, by which pulsars formed in tight binaries receive small kick velocities, may provide an innovative solution. In contrast to the DNS systems, for which high space velocities would indicate the presence of natal kicks during supernovae, low measured space velocities of the two MS-NS binaries may prove to be our best evidence for the natal kick hypothesis. At this stage, a high space velocity is almost certainly ruled out for J0045−7319 (Bell et al. 1995) and seems unlikely for B1259−63. The expected misalignment angle distribution of B1534+12 is quite sensitive to the applied kick model and may eventually prove useful in constraining the natal kick velocity distribution. Our preferred kick model predicts minimal misalignment of the pulsar's spin axis and the orbital angular momentum axis of the system. This, however, is inconsistent with recent observations at 1400 MHz of geodetic precession of B1534+12 by Arzoumanian (1995). We find that the best solution to the apparent contradiction between B1534+12's inferred space velocity and misalignment angle is to accept the natal kick hypothesis but to invoke constraints on the orbital separation of the binary at the instant of supernova.

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