Spin Tilts in the Double Pulsar Reveal Supernova Spin Angular-Momentum Production

Senior Thesis in Physics & Astronomy

Kyle Kremer

Advisor: Professor Vicky Kalogera

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Abstract

The radio-pulsar system PSR J0737-3039 is the only binary pulsar known to date to consist of two detectable radio pulsars (PSR J0737-3039 A and PSR J0737-3039 B). Apart from two spin magnitude measurements, this binary system is unique in providing us with measurements of spin orientation for both pulsars: pulsar A's spin is tilted from the orbital angular momentum by no more than 14 degrees at 95% confidence; pulsar B's by 130 ± 1 degrees at 99.7% confidence. Here we demonstrate that the significant difference between the two pulsar spin tilts requires that the supernova (SN) explosion that formed pulsar B must have produced a substantial off-centre kick imparted to the nascent pulsar, causing pulsar B to tumble to its current highly misaligned state. Using current constraints on the SN kick magnitude derived from the orbital and kinematic parameters of the system, and assuming that the kick is delivered as an instantaneous impulse, we calculate that the kick must have been displaced from the centre of mass of the exploding star by at least 1 km and more probably 5—10 km. Such offset distances are a significant fraction of the expected radii of nascent neutron stars. These offsets are necessary to tilt the spin of pulsar B to its current misalignment with respect to the orbital angular momentum (the precise offset depends on the kick magnitude and the spin of the pulsar progenitor). PSR J0737-3039 B is currently believed to have formed from an electron-capture supernova triggered in a massive O-Ne-Mg white dwarf. Regardless of the details of the kick mechanism and the process that produced pulsar B's current spin, the measured spin-spin misalignment in the double pulsar system provides for the first time an empirical, direct constraint on angular momentum production in supernovae. This constraint can be used to guide core-collapse simulations and the quest for understanding the spins and kicks of compact objects.

1 Introduction*

Binary star systems containing two neutron stars are of great interest to researchers in astrophysics. These systems provide a wealth of information in areas such as binary evolution, neutron star equations of state, and gravitational wave astronomy. When one or both of the neutron stars in the system are observed as pulsars, the system becomes even more valuable for research. Observations of such systems over several years have shown that the orbiting neutron stars are slowly losing energy, almost certainly due to the emission of gravitational waves, in accordance with the predictions of Einstein's theory of general relativity. Presently, seven observed double neutron star systems contain one pulsar (Wong et al. 2010).

In 2003 A.G. Lyne et al. discovered the first binary system (J0737-3039) containing two radio pulsars: PSR J0737-3039 A (Burgay et al. 2003) and PSR J0737-3039 B (Lyne et al. 2004). To this date, the radio-pulsar system J0737-3039 is still the only double pulsar. Pulsar A has a spin period of 22.7 milliseconds and a mass of 1.34 stellar masses, while pulsar B has a spin period of 2.8 seconds and a mass of 1.25 stellar masses (Table 1 gives the complete set of parameters for this system.)

This unique configuration of two pulsars has also permitted measurements of spin orientation for both pulsars (Ferdman et al. 2008; Lyutikov & Thompson 2005; Breton et al. 2008): pulsar A’s spin is tilted from the orbital angular momentum vector by no more than 14 degrees at 95% confidence (Ferdman et al. 2008); pulsar B’s by 130 degrees at 99.7% confidence. Such a measurement is not possible by a binary system other than a double pulsar. Here we argue that this large difference between the two pulsar spin tilts in the J0737-3039 system requires that the origin of most of pulsar B’s spin is connected to its supernova (SN) explosion; the spin of B’s progenitor, expected to be aligned with the pre-SN orbit due to tidal interactions, cannot be invoked to explain the present-day misaligned spin of pulsar B.

PSR J0737-3039 B is currently believed to have formed from an electron-capture supernova triggered in a massive O-Ne-Mg white dwarf (van den Heuvel 2004; Willems & Kalogera 2004; Piran & Shaviv 2005; Stairs et al. 2006; Wang et al. 2006; Willems et al. 2006; van den Heuvel 2007; Breton et al. 2008; Wong et al. 2010). Our results demonstrate that, whatever the details of its formation mechanism, the supernova that formed PSR J0737-3039 B produced the majority of its current spin. If the source of the present-day spin of pulsar B is a single, impulsive kick, then this kick must be off-center so that it tumbles the pulsar to its current orientation. Using constraints on the SN kick magnitude derived from the orbital and kinematic parameters of the system (Wong et al. 2010) we find that this kick must have been displaced from the center of mass of the exploding star by at least 1 km and probably 5–10 km. Such offset distances are a significant fraction of the expected radii of neutron stars. Off-center kicks were first suggested in Spruit & Phinney (1998) on purely theoretical grounds.

*The analysis and results presented here have been published already in *The Astrophysical Journal* (*Spin Tilts in the Double Pulsar Reveal Off-Centre Supernova Kick and Tumble.* Farr, W.M., Kremer, K., Lyutikov, M., and Kalogera, V. The Astrophysical Journal, **742,** 81 (2011)). In what follows I present the work much in the same way as in the refereed publication with additional material for explanations and clarity when necessary

2 Evolutionary History

When a massive star (several times heavier than the sun) has exhausted all of its nuclear fuel, the star's core will undergo core-collapse due to gravity. Depending upon the star's mass, this core-collapse can lead to a supernova explosion and the formation of either a neutron star or a black hole. Neutron stars with misaligned rotational and magnetic axes can emit radio-frequency radiation in a beam along the magnetic field axis. The rotation of the star causes the beam to sweep through space; if the alignment is right, we can observe a periodic series of radio pulses from the star as the beam sweeps past our line of sight. The pulsations of these objects, known as pulsars, allow for a precise measurement of the star's rotational frequency.

PSR J0737-3039 likely evolved from two stars originally massive enough to undergo supernova explosions and form two neutron stars (Tauris & van den Heuvel 2006) at the end of their nuclear lifetimes. Given the measured spin magnitudes and inferred magnetic fields (Burgay et al. 2003; Lyne et al. 2004; Ferdman et al. 2008; Lyutikov & Thompson 2005; Breton et al. 2008), pulsar A was the first-born neutron star, while pulsar B formed in a second SN. After the first pulsar was formed in the first SN event, the system passed through a high-mass X-ray binary phase. In this phase, pulsar A accreted matter from its companion. This accretion process transferred angular momentum to pulsar A contributing to this star's high spin period. Eventually, pulsar A's companion evolved off the main sequence and its expanding hydrogen envelope enveloped pulsar A. In this common envelope phase, tidal interactions between the two stars circularized the orbit and are expected (Tauris & van den Heuvel 2006) to have aligned the spins of pulsar A and of pulsar B's progenitor with the orbital angular momentum axis (perpendicular to the orbital plane). The transfer of orbital kinetic energy to the envelope eventually removed the outer layers of pulsar B's progenitor, leaving pulsar A in a tight orbit with the exposed helium-rich core of B's progenitor. After another brief period of mass transfer onto pulsar A (Dewi & van den Heuvel 2004; Willems & Kalogera 2004), the helium star exploded in the second SN, forming pulsar B. As a result of the multiple mass-transfer phases between the two SN events, just before pulsar B's SN the system was in a close, circular orbit with *both stars' spins aligned with the orbital angular momentum vector.*

Due to asymmetries associated with the SN ejecta (matter and/or neutrinos) SNe are thought capable of imparting a significant recoil impulse, a "kick", to any remnant surviving the explosion (see, e.g., Janka et al. (2008) and references therein). When a SN occurs in a binary system, thesekicks can significantly alter the orbital parameters or even disrupt the binary. The kick component directed parallel to the pre-SN orbital plane causes a change in the eccentricity and semi-major axis of the orbit; the component perpendicular to the pre-SN orbital plane can also cause a change in the inclination of the orbital plane. In the PSR J0737-3039 system, pulsar A's small spin-tilt angle (less than 14 degrees at 95% confidence using a two-pole emission model (Burgay et al. 2003; Lyne et al. 2004; Ferdman et al. 2008)) is indicative of a relatively small out-of-plane kick from the SN that formed pulsar B (Wong et al. 2010). Pulsar A's spin-orbit misalignment occurs only because the orbital plane is tilted by the SN kick. During the SN process, pulsar A's spin remains fixed in the inertial frame aligned with the pre-SN orbital angular momentum axis (Figure 1). Such a spin tilt for pulsar A occurs independently of the effects of the second SN on pulsar B's spin. In other words, the observed tilt of pulsar A's spin by itself does not require any change in the spin angular momentum of pulsar B relative to its progenitor. However, unless the SN contributes significant amounts of angular momentum to the nascent pulsar, the orientation of pulsar B's spin will be the same as its progenitor's spin, i.e. aligned with the pre-SN orbital plane and pulsar A's spin. Surprisingly, pulsar B's spin is in fact retrograde: tilted by $130.0^{+1.4}_{-1.2}$ degrees (99.7% confidence; Ferdman et al. 2008) relative to the current orbital angular momentum vector (see Figure 1).

3 The Need for Spin Angular Momentum from the Supernova

To produce pulsar B's retrograde spin, the SN must have significantly torqued pulsar B, causing it to tumble to the currently observed spin-orbit orientation. The pre-SN spin, $\mathbf{S}_0$, the angular momentum produced by the SN ejecta, $\Delta\mathbf{S}$, and the post-SN spin, $\mathbf{S}_{SN}$, are related by the conservation of angular momentum

$$\mathbf{S}_{SN} = \mathbf{S}_0 + \Delta\mathbf{S}. \quad \mathbf{(1)}$$

To determine $\Delta\mathbf{S}$, we must know $\mathbf{S}_0$ and $\mathbf{S}_{SN}$, but we only know the direction, not the magnitude, of $\mathbf{S}_0$ and the relationship between $\mathbf{S}_{SN}$ and the spin measured today is complicated by relativistic precession (Breton et al. 2008). However, we can still place constraints on $\Delta\mathbf{S}$. Relativistic precession causes the individual pulsar spins to precess about the total angular momentum of the system, which is approximately parallel to the orbital angular momentum. Such precession preserves the angle between the total angular momentum and the spin (which is the spin colatitude), but not the azimuthal orientation. Thus, the colatitude of $\mathbf{S}_{SN}$ relative to the normal to the current orbital plane is equal to the colatitude of the current spin—130 degrees. Based on the spin of pulsar A, the current orbital plane could be tilted at most 14 degrees relative to the pre-SN orbital plane. Therefore the colatitude of $\mathbf{S}_{SN}$ relative to the pre-SN orbital plane—and therefore relative to $\mathbf{S}_0$ —is at least 116 degrees. This is also the minimum angle between $\mathbf{S}_0$ and $\Delta\mathbf{S}$. The angular momentum produced by the SN must be significantly mis-aligned with the progenitor spin. To date, most SN simulations have focused on non-rotating progenitors (for example, see Blondin & Mezzacappa 2007; Rantsiou et al. 2011; Wongwathanarat et al. 2010); it remains to be seen whether the spin produced by the SN from the collapse of a rotating progenitor can be so significantly mis-aligned with the progenitor's rotation axis.

The typical moment of inertia (Spruit & Phinney 1998) of a neutron star is $0.36MR^2$; using pulsar B's measured mass of $1.25M_\odot$ (see Table 1) and a radius of 10 km, its current spin angular momentum is 2×10^{45} g cm^2 s^{-1}. Since this spin is retrograde whereas the pre-SN spin is roughly aligned (within 14°, given pulsar A's small spin tilt) with the current orbital plane, we can place a lower limit on the change of angular momentum needed to explain pulsar B's large and retrograde spin tilt,

$$\Delta\mathbf{S} \geq 2 \times 10^{45} \text{ g cm}^2 \text{ s}^{-1}, \quad (2)$$

where equality holds when $\mathbf{S}_0 = 0$. Because the angle between $\mathbf{S}_0$ and $\mathbf{S}_{SN}$ is greater than 90 degrees, any progenitor spin only increases the amount of angular momentum that must be added to the pulsar by the kick. This is demonstrated geometrically in Figure 2c.

The above discussion has been fully general. To extract more constraints from the observed spin-spin misalignment, we must make some assumptions about the origin of the pulsar spin. As a simplified model to elucidate the scales involved in this scenario, let us assume that the same impulsive kick (i.e. linear momentum) that changes the orbit of the system is also offset from the center of mass of pulsar B, and therefore applies a torque sufficient to produce the observed spin angular momentum. The kick and offset vectors must lie in the plane perpendicular to $\Delta\mathbf{S}$ (see Equation 3). The kick velocity, $\mathbf{v}_K$, the offset vector relative to the center of mass, $\mathbf{r}$, and the change in B's spin vector are related by

$$\Delta\mathbf{S} = \mathbf{r} \times \Delta\mathbf{p} = \mathbf{r} \times M_B\mathbf{v}_K, \tag{3}$$

where $\Delta\mathbf{p} = M_B\mathbf{v}_K$ is the change in linear momentum induced by a change in velocity of $\mathbf{v}_K$ in an object with mass M_B. The offset length r and kick velocity magnitude v_K must then satisfy the inequality

$$r \geq \frac{\Delta S}{M_B v_K}, \tag{4}$$

where $\Delta\mathbf{S}$ is the magnitude of the change of B's spin; the equality holds only when the kick and offset are perpendicular to each other.

The relative orientation of the current spin provides a constraint on the kick direction in this scenario. Let the colatitude of $\Delta\mathbf{S}$ relative to the pre-SN orbital plane be θ_Δ; because the angle between $\mathbf{S_0}$ and $\mathbf{S}_{SN}$ is greater than 90 degrees, no matter the magnitude of $\mathbf{S}_0$ we must have $\theta_\Delta \geq 116$ degrees. Let the plane perpendicular to $\Delta\mathbf{S}$ make an angle ψ with respect to the pre-SN orbital plane. Then we have $\psi = 180 - \theta_\Delta \leq 64$ degrees. The kick, $\mathbf{v}_K$, lies in this plane and therefore must have colatitude θ_K that satisfies

$$90 - \psi = 26 \leq \theta_K \leq 154 = 90 + \psi. \tag{5}$$

This geometry is illustrated in Figure 2. The constraint in Equation 5 is consistent with the constraint on kick colatitude in Figure 7 of (Wong et al. 2010), but tighter.

The constraint on the magnitude of the spin change, Equation (2), together with Equation (4), imply a lower limit on the offset distance

$$r \geq 3.2\ \left(\frac{25\ \mathrm{km\ s^{-1}}}{v_K}\right)\ \mathrm{km}. \tag{6}$$

If we assume that the core of pulsar B's progenitor was in synchronous, rigid-body rotation just before the supernova then ${S_0}^{SR} \simeq 2 \times 10^{45}\ \mathrm{g\ cm^2\ s^{-1}}$, and the limit on the offset distance rises by a factor of 1.8:

$$r_{SR} \geq 5.8\ \left(\frac{25\ \mathrm{km\ s^{-1}}}{v_K}\right)\ \mathrm{km}. \tag{7}$$

Wong et al. (2010) used the measured semi-major axis, eccentricity and proper motion of the J0737-3039 system (see Table 1) to constrain the kick imparted to the system by the second SN.

The Wong et al. (2010) analysis assumed that the pre-SN orbit was circular and that the system came from a progenitor population with number density

$$n(R,z) = n_0 \exp\left(-\frac{R}{h_R}\right) \exp\left(-\frac{|z|}{h_z}\right) \tag{8}$$

with h_R = 2.8 kpc and h_z = 0.07 kpc the galactic scale length and height, respectively, moving with the local galactic rotation velocity. The SN kick and mass loss must then induce the current eccentricity and semi-major axis in the orbit and give the system as a whole a velocity such that it moves in the galactic potential to its current location in the 100 to 200 Myr since the second SN (Lorimer et al. 2007). Because of the uncertainty in the amount of mass loss, pre-SN semimajor axis, pre-SN galactic location, the age of the system, and the measurement uncertainty in the current orbital parameters, a range of kick magnitudes between 0 and 60 km/s is allowed in the Wong et al. (2010) analysis (Wong et al. 2010, Figure 5). In Figure 3 we show the probability distribution of minimum offset distances implied by this distribution of kick velocities. Even for large kick velocities, the minimum offset distance exceeds ~ 1 km. For the smallest allowed kicks, the minimum offset distances exceed the current ~ 10 km radius of the neutron star.

The magnitude of the offset, r, required to produce the needed Δ**S** depends on the relative orientation of the offset and kick, $\mathbf{v}_K$. If the angle between **r** and $\mathbf{v}_K$ in the plane perpendicular to Δ**S** is θ_{rK}, then

$$r = \frac{\Delta S}{M_B v_K \sin\theta_{rK}} \tag{9}$$

which is larger than the minimum offset distance by a factor of $(\sin\theta_{rK})^{-1}$ (see Equation 3). Kicks that are nearly aligned with the radial vector (small θ_{rK}) require arbitrarily large off-center distances to match the current spin orientation. Even modest misalignments of 40 degrees give an enhancement factor of $\sin^{-1} 40 \sim 1.6$ over the offset for perpendicular **r** and $\mathbf{v}_K$.

4 Discussion

Multi-dimensional simulations (Blondin & Mezzacappa 2007) of core-collapse SNe have shown that an instability in a stationary accretion shock (SASI) may provide a method of depositing a substantial amount of spin angular momentum (2×10^{47} g cm^2 s^{-1}.) onto a proto-neutron star as part of the collapse process itself and separate from any rotation of the progenitor. (In fact, the simulations of Blondin & Mezzacappa (2007) used non-rotating progenitors.) This would be more than enough angular momentum to account for the observed spin angular momentum of pulsar B (2×10^{45} g cm^2 s^{-1}.). The general consensus from recent evolutionary studies (van den Heuvel 2004; Willems & Kalogera 2004; Podsiadlowski et al. 2005; Stairs et al. 2006; Wang et al. 2006; Willems et al. 2006; van den Heuvel 2007; Breton et al. 2008; Wong et al. 2010) is that pulsar B was formed in an electron-capture SN, where an iron core is never formed and instead core collapse is initiated through electron captures onto Ne/Mg nuclei (Dessart et al. 2006; Kitaura et al. 2006; Podsiadlowski et al. 2004; Miyaji et al. 1980; Nomoto 1984, 1987). During the course of such a collapse, the proto-neutron star shrinks from a radius of ~ 100 km to ~ 10 km.

We emphasize that the assumption of the foregoing discussion that the kick is applied at a single location is simplistic (see, e.g., Spruit & Phinney (1998)); in a real supernova, both linear and angular momentum will be accumulated by the proto-neutron star throughout its formation at many different locations. In this more realistic context, the constraints above on offset distances should be interpreted instead as constraints on the offset scale at which the *bulk* of the linear and angular momentum is accumulated. More precise constraints will require detailed modeling of the hydrodynamic process of momentum accumulation in the supernova that formed PSR J0737-3039B. Nevertheless, it is interesting that the location of kicks inferred from such a simple model is consistent with kick origins in the bulk of the shrinking proto-neutron star during the supernova (see Figure 3). Some recent SN modeling suggests that the processes that produce the kick and those that impart rotation to the resulting neutron star produce independent kicks and spins, and therefore there is little correlation between the kick magnitude and direction and the rotation imparted to the post-SN compact object (Wongwathanarat et al. 2010; Rantsiou et al. 2011). In this case the offset length scale inferred above from the dynamical constraints on the kick would not be relevant. We conclude that *only if* pulsar B's spin is actually linked to the torque induced by the physical mechanism producing the kick it must be offset from the center of mass of the collapsing neutron star progenitor.

Regardless of the specifics of the collapse process, however, the expected alignment of the spin of pulsar B's SN progenitor with the pre-SN orbital angular momentum and the observed misalignment of pulsar B's spin and orbit at present uniquely imply that pulsar B's spin is dominated by angular momentum produced during the SN process, not angular momentum provided by the progenitor. The realization of this empirical constraint on angular momentum production in supernovae presented here is uniquely enabled by the spin spin misalignment in the PSR J0737-3039 system (Lyne et al. 2004; Ferdman et al. 2008; Lyutikov & Thompson 2005) and can be used to guide core-collapse simulations and the quest for the understanding of compact object spins and kicks.

Distance	600 pc
Galactic Latitude	245.2 deg
Galactic Longitude	-4.5 deg
Proper Motion	10 km/s
Spin Period (A)	22.7 ms
Spin Period (B)	2.8 s
Mass (A)	1.34 $M_\odot$
Mass (B)	1.25 $M_\odot$
Spin-orbit misalignment (A) (Ferdman et al. 2008)	< 10 deg
Spin-orbit misalignment (B) (Lyutikov & Thompson 2005; Breton et al. 2008)	130 deg
Orbital Period	2.4 hrs
Semi-Major Axis	1.26 $R_\odot$
Eccentricity	0.0878

Table 1: J0737-3093 System Parameters. Except as noted above, system parameters are from Burgay et al 2003; Lyne et al. 2004.

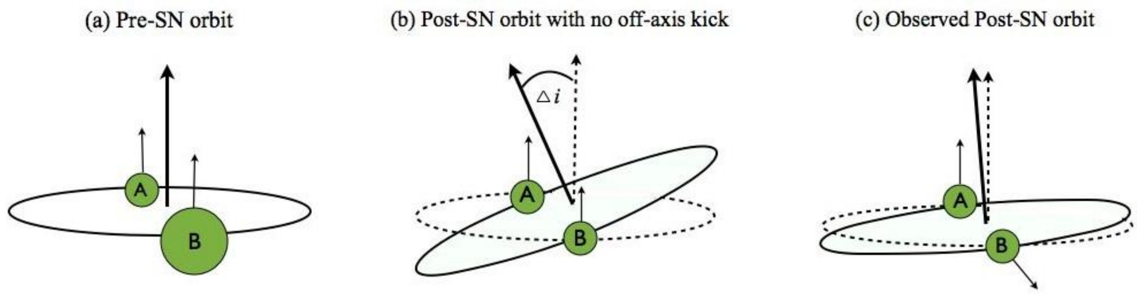

Figure 1— Effect of SN kick on binary orbit. The pre-SN orbit containing pulsar A and pulsar B's progenitor is shown in (a). The effect of an on-center SN kick that slightly changes the inclination of the orbit is illustrated in (b). Notice the post-SN alignment of the two pulsars' spin axes. Part (c) illustrates the present-day orbit with a 130 degree misalignment between pulsar B's spin axis and the orbital axis.

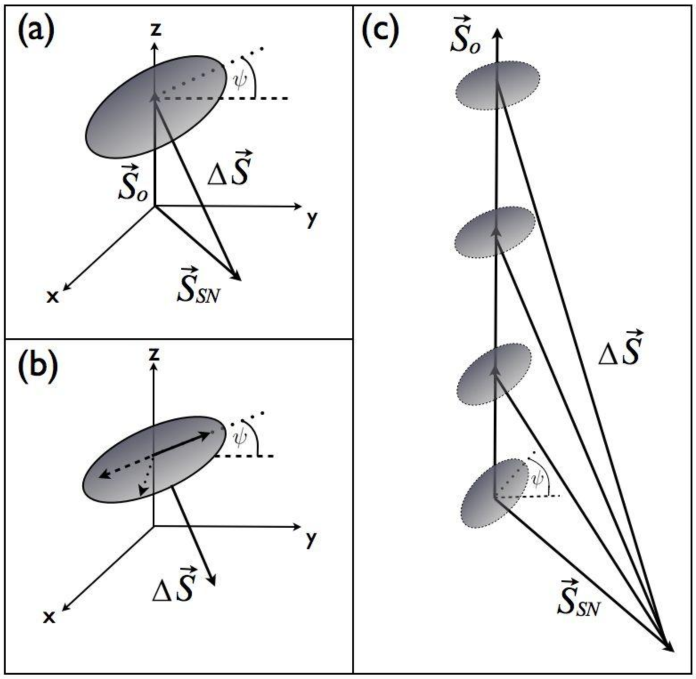

Figure 2— Geometry of the angular momentum change due to an off-center kick imparted to the nascent pulsar. The *x-y-z* reference frame is anchored on pulsar B at the time of its SN; the *x-y* plane is the pre-SN orbital plane. In panel (a) we show the relationship between $\mathbf{S}_0$, $\mathbf{S}_{SN}$, and $\Delta\mathbf{S}$ and the orientation of the plane orthogonal to $\Delta\mathbf{S}$ (which is inclined by an angle ψ with respect to the orbital plane). In panel (b) we show that vectors lying in the plane orthogonal to $\Delta\mathbf{S}$ — like $\mathbf{v}_K$—can have an inclination with respect to the orbital plane that varies between $-\psi$ and ψ, leading to the constraint on the colatitude of $\mathbf{v}_K$ of $90 - \psi \leq \theta_K \leq 90 + \psi$ found in Equation (5). In panel (c) we show that as the magnitude of $\mathbf{S}_0$ increases, $\Delta\mathbf{S}$ increases in magnitude (see Equation (2)) and tilts toward the south pole, reducing ψ. Therefore, the most conservative constraints on θ_K are obtained when $\mathbf{S}_0 = 0$, giving $26 \leq \theta_K \leq 154$ as in Equation (5).

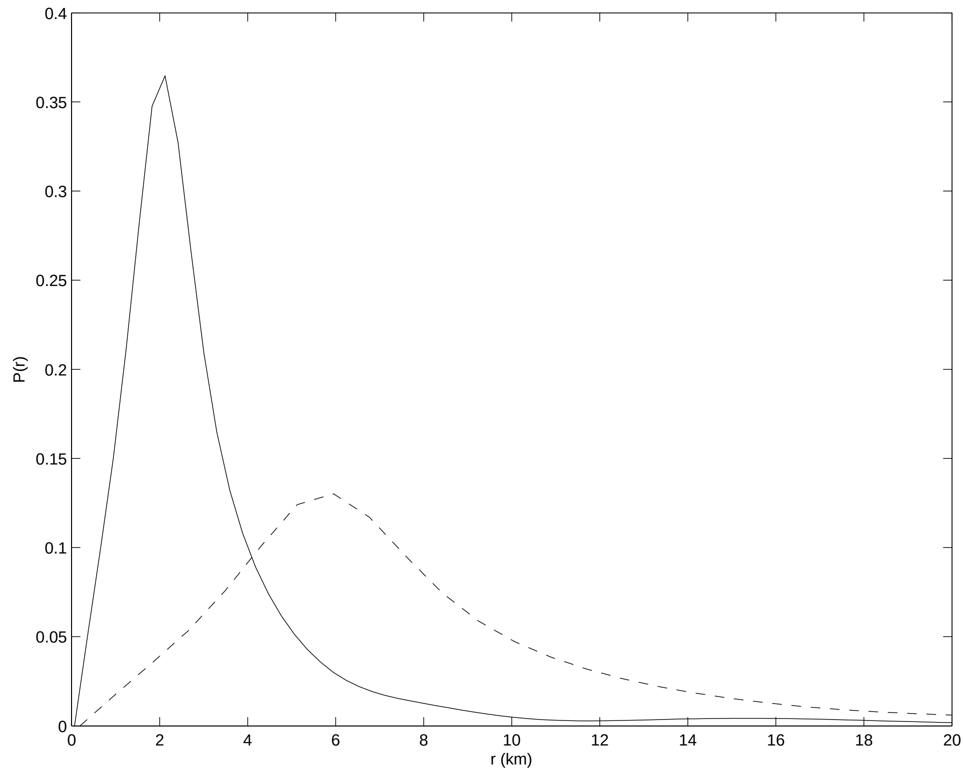

Figure 3— Distributions of minimum offset distances implied by the current orbital constraints (Wong et al. 2010) on kick magnitudes (see Equation (6)). The solid line gives the distribution assuming that $\mathbf{S}_0 = 0$, with a kick that is orthogonal to the offset vector. The dashed line assumes that the core of pulsar B's progenitor was in synchronous, rigid-body rotation just prior to the supernova ($S_0 = S_0^{SR} \simeq 2 \times 10^{45}$ g cm^2 s^{-1}) and that the kick-offset angle is 40 degrees.

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