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# STUDIES OF THE RELATIVISTIC BINARY PULSAR PSR B1534+12. II. ORIGIN AND EVOLUTION

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## ABSTRACT

We have recently measured the angle between the spin and orbital angular momenta of PSR B1534+12 to be either $25 \pm 4^\circ$ or $155 \pm 4^\circ$. This misalignment was almost certainly caused by an asymmetry in the supernova explosion that formed its companion neutron star. Here we combine the misalignment measurement with measurements of the pulsar and companion masses, the orbital elements, proper motion, and interstellar scintillation. We show that the orbit of the binary in the Galaxy is inconsistent with a velocity kick large enough to produce a nearly antialigned spin axis, so the true misalignment must be $\sim 25^\circ$. Similar arguments lead to bounds on the mass of the companion star immediately before its supernova: $3 \pm 1 M_\odot$. The result is a coherent scenario for the formation of the observed binary. After the first supernova explosion, the neutron star that would eventually become the observed pulsar was in a Be/X-ray type binary system with a companion of at least 10–12 $M_\odot$. During hydrogen (or possibly helium) shell burning, mass transfer occurred in a common envelope phase, leaving the neutron star in a roughly half-day orbit with a helium star with mass above $\sim 3.3 M_\odot$. A second phase of mass transfer was then initiated by Roche lobe overflow during shell helium burning, further reducing both the helium star mass and orbital period before the second supernova. Scenarios that avoid Roche lobe overflow by the helium star require larger helium star masses and predict space velocities inconsistent with our measurements. The companion neutron star experienced a velocity kick of $230 \pm 60$ km/s at birth, leading to a systemic kick to the binary of $180 \pm 60$ km/s. The direction of the kick was roughly opposed to the instantaneous orbital velocity of the companion, but the kick angle is largely unconstrained.

*Subject headings:* pulsars: individual (PSR B1534+12)—supernovae

## 1. INTRODUCTION

The handful of known short-period double neutron star binaries are of interest to physicists and astrophysicists working in a wide variety of fields. Most famously, studies of two of these systems have been used as laboratories to test aspects of fundamental gravitation theory that are inaccessible in the solar system, including the prediction by Einstein (1916) of the production of gravitational radiation (Taylor & Weisberg 1989; Stairs et al. 2002). Such binaries, in their late stages of gravitational inspiral, are among the most likely sources to be detected by LIGO and other gravitational wave observatories (Abbott et al. 2004, and references therein). They yield high-precision mass measurements that have been used to study the neutron star equation of state (Thorsett & Chakrabarty 1999). Finally, they are important long-lived relics of binary evolution that preserve in their orbital elements a memory of short-lived mass transfer phases that are rarely if ever observed in progress (e.g., Bhattacharya & van den Heuvel 1991).

A complicating factor in understanding the birthrate of these binaries has been constraining asymmetries in supernova explosions. Isolated radio pulsars are observed to have high space velocities, interpreted as evidence that newborn neutron stars receive a momentum kick at birth (Dewey & Cordes 1987; Lyne & Lorimer 1994). There is some evidence that kicks given to stars in binaries are smaller (Camilo et al. 1994; Cordes & Chernoff 1997; Portegies Zwart & Yungelson 1998; Hughes & Bailes 1999), but it is unclear whether this is a selection bias related to the probability of binary survival, or whether these stars truly have a different kick distribution, perhaps because of a different angular momentum at collapse. Since kicks introduce new degrees of freedom in the change of the binary elements after the supernova event, understanding kicks is also important for estimating the pre-supernova orbital properties. Finally, asymmetries can produce misalignments between the spin and orbital angular momenta in the binary, which can lead to changes in the gravitational-wave signature at merger (Apostolatos et al. 1994; Grandclément et al. 2003). Misalignment also makes possible the study of general relativistic (geodetic) precession, providing a qualitatively new test of strong field gravity theories (Damour & Ruffini 1974; Barker & O'Connell 1975; Barker & O'Connell 1975; Esposito & Harrison 1975; Damour & Taylor 1992; Stairs et al. 2004).

Recently, we have used precession measurements (together with the assumption that general relativity correctly describes the kinematics of neutron star binaries) to measure the misalignment angle in the PSR B1534+12 binary (Stairs et al. 2004). By combining this result with our previous high precision measurements of the orbital elements, component masses, system distance, and

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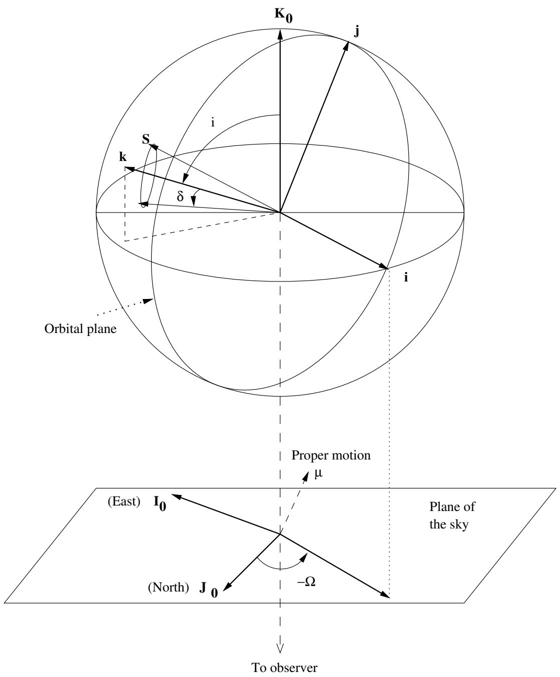


FIG. 1.— The geometry of the PSR B1534+12 orbit. The orbital angular momentum vector is **k**, and the spin axis is **S**. The precession cone, with half-opening angle $\delta$, is shown. The vector **i** is directed towards the ascending node.

proper motion, and with a measurement of the orientation of the orbit from interstellar scintillation studies, we are able to tightly constrain the magnitude and direction of the asymmetric velocity kick imparted to the pulsar's companion when it was formed. Three unknown parameters—the line-of-sight velocity of the binary, the pre-supernova orbital size, and the pre-supernova mass of the companion—are all tightly constrained. These in turn strongly constrain the evolutionary history of the binary, at least during the period between the first and second supernovae, as well as the supernova asymmetry.

Our work here draws on previous studies of several relativistic binaries, particularly of this system and of PSR B1913+16. However, the quality and extent of the data for PSR B1534+12 now far exceeds what is available for the other binaries, allowing much more robust conclusions to be drawn. We describe these data in §2. In §3 we review the generic evolution of a compact binary system before, during, and after the second supernova event. In §4, we combine observations with theory to constrain the particular history of the PSR B1534+12 binary.

## 2. OBSERVATIONS OF PSR B1534+12

As we will see below, the current orbit and kinematics of the PSR B1534+12 binary were largely determined by the properties of the binary just prior to the second supernova event (which created the neutron star companion to the observed pulsar) and by the mass loss and momentum imparted to the system during the second supernova. Neither the size nor the eccentricity of the orbit have changed significantly since that event, while the binary has moved ballistically through the Galactic gravitational potential and gyroscopically maintained the direction of its orbital angular momentum vector. A wealth of data fully constrain the current orbital properties, including the orientation of the orbit on the sky. (See Fig. 1 for a reference to angles describing the orientation.) The distance and transverse components of the binary velocity are also well constrained. Only the radial velocity and the age cannot be directly determined, though a rough upper limit can be placed on the time since the second supernova.

### 2.1. *Orbital elements and masses*

Radio pulsar timing has produced exquisitely accurate estimates of the orbital elements of the PSR B1534+12 binary. The system is essentially a single-line spectroscopic binary, with the Doppler shift of the pulsar period replacing the usual Doppler shift of a stellar spectral line. Although only line-of-sight velocity variations can be observed through timing, the measurement of general-relativistic corrections to the Keplerian orbital equations allow the orbital inclination and component masses to be determined. The timing experiments, analysis, and results have been described in extensive detail in Stairs et al. (2002). For our current purposes, it is sufficient to know the orbital period $P_b = 0.421$ days, eccentricity $e = 0.274$, relative semimajor axis $a = 7.62$ light seconds, orbital inclination $\sin i = 0.975$, pulsar mass $m_1 = 1.333 M_\odot$, and companion mass $m_2 = 1.345 M_\odot$. In all cases, the uncertainty is small relative to the last quoted digit.

### 2.2. *Misalignment of spin and orbital angular momenta*

Misalignment between the pulsar spin axis and the orbital angular momentum axis causes the spin axis to precess around the orbital axis at a rate of $0.51°/\text{yr}$. This so-called geodetic precession is a simple relativistic consequence of the parallel transport of the spin vector in curved space; it is a consequence of the same angle deficit that produces precession of the periastron of the orbit.

Precession of the pulsar spin axis causes the impact angle between the observer's line of sight and the pulsar's magnetic pole to change, with an amplitude that depends on the misalignment angle $\delta$ between the spin and orbital angular momenta. This shifting viewing angle causes changes in the apparent pulsar beam shape and polarization properties.

Recently, we have used a long-term study of the polarization and beam shape to measure $\delta = 25.0 \pm 3.8°$ (Stairs et al. 2004). There is a discrete ambiguity that corresponds to reversing the spin direction, so $\delta = 155.0 \pm 3.8°$ is also allowed.

### 2.3. *Position and velocity*

In addition to the orbital elements, timing measurements provide very accurate estimates of the pulsar position and proper motion, through the annual modulation of the observed pulse period caused by the Earth's motion. In the case of PSR B1534+12, the distance can also be estimated from a measurement of the apparent orbital period derivative (after correction for the contribution due to gravitational radiation emission)—which is caused by a combination of acceleration in the Galactic potential and apparent acceleration along the line of sight that arises from the transverse motion.

The binary's current position is well out of the Galactic plane, at $l = 19.8°$, $b = 48.3°$. The distance is

$d = 1.02 \pm 0.05$ kpc. The observed proper motion is $\mu_{\rm RA} = 1.3$ mas/yr, $\mu_{\rm dec} = -25.1$ mas/yr (Stairs et al. 2002). The total proper motion is $\mu = 25.2$ mas/yr, directed towards a Galactic position angle $239.2^\circ$, which at the known distance implies a transverse velocity (uncorrected for Solar motion) of 122 km/s. In contrast to the usual case with a spectroscopic binary, there are no direct constraints available on the radial component of the space velocity as the rest-frame spin period of the pulsar is unknown.

In projection, the pulsar appears to be moving towards the plane, with a $b$-component velocity $-62$ km/s. However, a radial velocity component of just 56 km/s is sufficient to reverse the apparent motion, so it is unknown whether the pulsar is presently moving towards or away from the plane.

### 2.4. *Scintillation*

Timing studies, which measure the component of velocity along the line sight, are insensitive to rotations of the binary orbit around the line of sight, and hence the angle $\Omega$ of the ascending node on the plane of the sky.[1] This angle is accessible through proper-motion-induced changes in the projected orbital size, with $\dot{x}/x = \mu \sin j \cot i$, with $i$ the orbital inclination and $j$ the angle between the proper motion direction and $\Omega$ (Arzoumanian et al. 1996). Because $\mu$ is small for PSR B1534+12, this has not yet been measurable.

In principle, some constraint on the direction of the pulsar's spin axis could be obtained from polarization studies, if corrections are made for Faraday rotation and observations are properly calibrated against an absolute reference source. This has also not yet been done for PSR B1534+12.

An alternative approach that has been successful for this source comes from study of diffractive scintillation. The propagation of the pulsar signal through the inhomogeneous interstellar medium produces a pattern ("screen") of intensity variations caused by constructive or destructive interference. The speed at which this screen sweeps past the observer is proportional to the vector sum of the Earth's motion, the binary's proper motion, and the pulsar's orbital motion, and is inversely proportional (at least statistically) to the decorrelation timescale for intensity variations (Lyne 1984; Dewey et al. 1988).

By measuring the decorrelation timescale as a function of orbital phase, Bogdanov et al. (2002) were able to measure $\Omega = 70 \pm 20^\circ$ or $290 \pm 20^\circ$, reckoned north through east. The solutions correspond to $\cos i < 0$ and $\cos i > 0$, respectively;[2] only the second is consistent with our polarization studies (Stairs et al. 2004). Although the uncertainties remain large, we will see that the resulting constraint on the direction of the orbital angular momentum is useful.

### 2.5. *Age*

A simple estimate for the age of the binary since the second supernova is given by the characteristic age of the observed pulsar: $\tau_c \equiv P/2\dot{P} = 0.25$ Gyr. The true age $\tau$ is unknown. If the pulsar was born at or below the spin-up line and has evolved by magnetic dipole braking (with braking index $n = 3$), then $\tau \lesssim 0.21$ Gyr (Arzoumanian et al. 1999). The age could be significantly less than this if the pulsar spin-up ended before the spin-up line was reached, or if mass transfer ended (and spin-down began) well before the second supernova, and could be somewhat larger if $n < 3$. As will be discussed in §4.2, ages as small as 10 Myr allowed if the binary is just leaving the plane for the first time. If the system is truly that young, the companion star may still be an active radio pulsar, which cannot be ruled out if the Earth lies outside the path of its lighthouse beam. We believe it is unlikely that the age of the binary is much larger than the characteristic age. The direct constraints on effective braking indices for pulsars with intermediate magnetic fields, like PSR B1534+12, is limited. However, Brisken et al. (2003) have found that characteristic ages and kinematic ages agree well in a set of high field pulsars, and in a sample of millisecond pulsars (with smaller magnetic fields), Camilo et al. (1994) found that half had characteristic ages larger than a Hubble time, implying that characteristic ages were typically an overestimate of true age. Without further information, we take $2.1 \times 10^8$ yrs as a rough upper limit to the age of the system, but none of our conclusions depend strongly on that limit.

## 3. THE EVOLUTION OF THE PSR B1534+12 BINARY

In general terms, the formation of close double neutron star binaries like PSR B1534+12 is well understood (see Bhattacharya & van den Heuvel 1991, for example, for a review). It begins with a first supernova in a binary star system, in which the neutron star that is now observed as a pulsar was born. After a possible Be/X-ray binary phase, a period of mass transfer occurs: "case B" if it occurs by Roche lobe overflow during hydrogen shell burning, as the companion first climbs the giant branch, or "case C" if it occurs during helium shell burning. ("Case A" transfer, while the companion is still on the hydrogen main sequence, is thought to lead to destruction of the binary through merger.) During the ensuing common envelope evolution, the system spirals together, leaving a binary containing a neutron star and a bare helium star. After case B transfer, the helium star is unevolved. After case C transfer, the helium star has already developed a carbon-oxygen core. A second stage of mass transfer may occur, which is again called case A, B, or C if it occurs during helium core burning, helium shell burning, or carbon burning, respectively. The overall mass-transfer history is, for example, case BB if a first phase occurred during hydrogen shell burning and a second during helium shell burning. In any case, during mass transfer the orbit is circularized and the pulsar is spun-up, or "recycled," and the pulsar spin axis aligned with the orbital angular momentum. Finally, a second supernova explosion produces the companion neutron star, which may live for $\sim 10^7$ yrs as a pulsar. (The faster, recycled pulsar can live $\gtrsim 10^9$ yrs, so most observed double-neutron star binaries are similar to B1534+12, with only the recycled pulsar visible,

[1] Note that we use the standard convention in binary pulsar studies and define the "ascending node" as the node at which the observed pulsar is moving away from the observer.

[2] Although Bogdanov et al. (2002) do not explicitly identify which solution corresponds to which sign of $\cos i$, our independent analysis has been confirmed by Bogdanov, private communication.

and only in rare cases like the recently discovered PSR J0737−3039 (Lyne et al. 2004) can both pulsars be seen.)

Brown (1995) proposed an alternative scenario in which the initial inspiral of two stars of similar mass produces a double helium star binary. Though different in the early phases of evolution, this scenario still requires mass transfer after the first supernova in order to recycle the observed pulsar, so the system just prior to the second supernova is again expected to be a close, circular neutron-star–helium-star binary with the pulsar spin and orbital angular momenta aligned. We will not further discuss this possible evolutionary track, except to note that because the late evolution is very similar to the standard scenario most of our conclusions would be unchanged.

At this point, it is important to emphasize that the immediate progenitors of systems like PSR B1534+12—that is, close binaries that contain a neutron star and bare helium star—are not observed, with the possible exception of Cyg X-3, which appears to be a Wolf-Rayet star in orbit around either a neutron star or a black hole (van Kerkwijk et al. 1992; Fender et al. 1999). Our primary observational constraints on the late stages of the standard evolutionary scenario are the properties of the resulting double neutron star binaries, including their masses, orbital elements, and space motions. In the case of PSR B1534+12, a number of studies have already been done (Yamaoka et al. 1993; Fryer & Kalogera 1997; Arzoumanian et al. 1999; Francischelli et al. 2002; Dewi & Pols 2003; Willems et al. 2004). To these, we now add improved estimates of the pulsar distance and proper motion (Stairs et al. 2002), measurement of the spin-orbit misalignment (Stairs et al. 2004), and measurement of the line of nodes angle (Bogdanov et al. 2002), which together strongly constrain the magnitude of any asymmetric kick applied to the companion star during the supernova in which it was born.

### 3.1. *The pre-supernova binary*

A number of constraints on the properties of the presupernova binary come from the size of the helium star companion, the core mass required to form a neutron star, and the possible stellar evolution and mass transfer histories that could produce the close binary. A detailed study of the evolution of close helium star binaries has recently been carried out by Dewi et al. (2002) and Dewi & Pols (2003), and we draw heavily from their work.

The small size of the pre-supernova binary—far too small to contain two main sequence stars—immediately implies that the orbit went through at least one mass transfer and inspiral phase. In the standard model, the system after the first supernova is a Be/X-ray type binary that spirals together in a common envelope phase during either case B or case C mass transfer. (As noted above, an alternate model posits inspiral during a double helium star phase before the first supernova.)

The subsequent evolution depends on the helium star mass and whether a second mass transfer phase occurs. As discussed in Dewi et al. (2002), case BA mass transfer, during helium core burning, never results in a double neutron star binary. Low mass stars lose enough mass that they leave CO white dwarf remnants, rather than collapsing to neutron stars. High mass stars experience dynamically unstable Roche lobe overflow, and probably coalesce with the neutron star to form an isolated black hole.

Case BB mass transfer, during helium shell burning, results in the removal of the helium star's envelope and the formation of a CO or ONe white dwarf if the zero age helium star mass is less than $2.5M_\odot$. Stars with mass less than $3.3M_\odot$ (or $3.8M_\odot$ in orbits below about six hour period) spiral in during a common envelope phase, and probably produce very compact (15 minute) double neutron star binaries, which have very short merger times and are therefore difficult to detect (Dewi & Pols 2003). More massive stars, up to about $6.5M_\odot$, avoid a common envelope during Roche lobe overflow, and hence avoid catastrophic inspiral. After mass transfer, these systems have orbital periods of hours to days, and pre-supernova core masses between about 2.2 and $4M_\odot$. As we will see, these are progenitors for systems like PSR B1534+12.

Larger helium stars don't swell significantly as they evolve, so avoid Roche lobe overflow. Binaries containing such massive He stars never experience Roche lobe overflow, and are also possible progenitors of double neutron star binaries. In this case, the spin-up of the observed pulsar occurs by accretion from the helium star wind. In this scenario, a lower limit on the zero age helium star mass comes from the requirement that it never expand into contact with its Roche lobe, and an upper limit comes from the requirement that its zero age radius fit within the Roche lobe. In the specific case of PSR B1534+12, Dewi & Pols (2003) have found that although a fairly wide range of zero age helium masses are possible (up to about $13M_\odot$), after wind losses there is only a very limited range of pre-supernova mass possible: $5 \pm 0.5M_\odot$. As we will see, supernovae in these systems can reproduce the observed orbit of PSR B1534+12, but only with a kick too large to be consistent with the observed space velocity. There are no possible scenarios for the formation of PSR B1534+12 that begin with case C transfer and then avoid Roche lobe overflow.

### 3.2. *The second supernova event*

We denote the orbital eccentricity, relative semimajor axis, and total mass before the second supernova by $e_i$, $a_i$, and $M_i = m_1 + m_{2i}$, where $m_i$ is the mass of the observed pulsar and $m_{2i}$ is the presupernova mass of the companion. Before the second supernova explosion, the mass transfer that spun-up PSR B1534+12 also almost certainly circularized the binary orbit, so we take $e_i = 0$. The orbital velocity just prior to the supernova is $\vec{V}_i$; from Kepler's laws the (constant) orbital speed is given by $V_i^2 = GM_i/a_i$. During the explosion, mass $M_i - M_f = m_{2i} - m_{2f}$ is lost from the system, and a velocity kick $\vec{V}_k$ (the "natal kick") is applied to the companion star. After the explosion, the new elements are $e_f$, $a_f$, and $M_f = m_1 + m_{2f}$, and the change in the direction of the orbital angular momentum is $\delta$. Expressions for the postexplosion elements can be found in Hills (1983). For convenience, we follow the very clear exposition of Wex et al. (2000) and define normalized quantities $\tilde{v} = \vec{V}_k/V_i$, $\alpha \equiv a_f/a_i$, $\beta = M_f/M_i$, and $\eta = \sqrt{\alpha\beta(1-e_f^2)}$. Then the shifts in the elements can be related to the components of the kick velocity vector through:

$$\tilde{v}_x = \pm\eta \left[ \left(1 - \frac{1}{\alpha\,(1+e_f)}\right) \left(\frac{1}{\alpha\,(1-e_f)} - 1\right) \right]^{1/2} \quad (1)$$

$$\tilde{v}_y = \eta \cos\delta - 1 \quad (2)$$

$$\tilde{v}_z = \pm\eta \sin\delta. \quad (3)$$

Here the $\hat{x}$ axis is the line connecting the pulsar and companion at the time of the explosion, $\hat{y}$ is the direction of instantaneous velocity of the companion, and $\hat{z}$ is perpendicular to the orbit. From equation 1 it is straightforward to see that the initial semimajor axis is bounded by

$$\frac{1}{1+e_f} \le \alpha \le \frac{1}{1-e_f}. \quad (4)$$

For any $\alpha$ in this range, $\beta < 1$, and $\delta$, we can use equations. 1–3 to calculate the kick velocity vector needed to produce the observed system.

Given the mass loss and kick applied to the companion star, the resulting kick to the binary center of mass $\tilde{u} = \vec{u}/V_i$ can also be calculated. We refer to this as the "systemic kick." (Note that the binary receives a systemic kick even in a symmetric explosion, when $\vec{V}_k = 0$.) Again, we follow Kalogera (1996) and Wex et al. (2000) and write

$$\tilde{u}^2 = \kappa_1 + \kappa_2 \left(2 - \alpha^{-1}\right) - \kappa_3 \sqrt{\alpha \left(1 - e_f^2\right)} \cos\delta, \quad (5)$$

where

$$\kappa_1 \equiv \frac{m_{2i}^2}{M_i^2}, \quad \kappa_2 \equiv \frac{m_{2f}^2}{M_i M_f}, \quad \text{and} \quad \kappa_3 \equiv 2\sqrt{\kappa_1 \kappa_2}. \quad (6)$$

We can decompose this into the component perpendicular to the post-supernova orbit $\tilde{u}_\perp$ and the component in the plane of the orbit $\tilde{u}_\parallel$, with

$$\tilde{u}_\perp = \sqrt{\kappa_1} \sin\delta \quad (7)$$

and

$$\tilde{u}_\parallel^2 = \kappa_1 \cos^2\delta + \kappa_2 \left(2 - \alpha^{-1}\right) - \kappa_3 \sqrt{\alpha \left(1 - e_f^2\right)} \cos\delta, \quad (8)$$

### 3.3. *Evolution after the second supernova*

The current binary system consists of two neutron stars. The orbit evolves slowly as it loses energy and angular momentum to gravitational radiation. Neither mass transfer nor tidal effects will have any significant contribution to the orbital evolution until the last stages of inspiral, about 3 Gyr from now.

Although high precision radio pulsar timing observations have measured the effects of gravitational radiation damping on the orbital elements, they are very small. Indeed, the total change in the elements since the second supernova explosion formed the double-neutron star binary can for most purposes be ignored. Following Peters (1964), we can write the fractional rates of change of the semi-major axis and eccentricity as:

$$\frac{1}{a}\frac{da}{dt} = -\frac{64G^3}{5c^5} \frac{m_1 m_2 M}{a^4 \left(1 - e^2\right)^{7/2}} \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right) \quad (9)$$

and

$$\frac{1}{e}\frac{de}{dt} = -\frac{304G^3}{15c^5} \frac{m_1 m_2 M}{a^4 \left(1 - e^2\right)^{5/2}} \left(1 + \frac{121}{304}e^2\right). \quad (10)$$

For PSR B1534+12, the timescales for evolution of $a$ and $e$ are 9.0 Gyr and 2.0 Gyr, respectively: both much longer than the pulsar characteristic age. We can therefore ignore post-supernova evolution of the orbital elements. As we will see, we are actually interested only in $a$ and in $1 \pm e$. Although we can't properly correct these quantities to their original values without knowing the true binary age, the errors that enter when we neglect radiation damping are $\lesssim 3\%$, which will be dwarfed by uncertainties in stellar modeling.

Because tidal effects are extremely small, no gravity-driven evolution of $\delta$ is expected. Recently, Demorest et al. (2004) have suggested that wind from the fast pulsar in the PSR J0737−3039 binary, which penetrates well into the light-cylinder of the slower pulsar, may have aligned the spin axis of the slow pulsar with the orbital angular momentum. Such alignment is unlikely for a fast pulsar like B1534+12; for any likely birth luminosity, the standoff radius would have been well outside the light cylinder of B1534+12. The orbital motion dominates the total angular momentum of the system, so the orientation of the orbit remains nearly fixed in space, while the spin axis of the pulsar precesses around it tracing a cone with half opening angle $\delta$.

In summary, because of its small age and slow evolution, we can without significant error take the currently observed orbital parameters, orbital orientation, and spin-orbit misalignment to be an accurate record of the state of the system immediately after the second supernova explosion. The space velocity imparted to the system during the second supernova is not, however, preserved as the binary moves through the Galactic potential. We discuss this complication in §4.2.

## 4. DISCUSSION

Our goal is to combine the wealth of observational data on the current state of the binary system and its position and motion through the Galaxy with constraints that come from binary evolution modeling and the effects of the mass loss during the supernova event to develop a consistent model of the late evolution of the system. Several free parameters remain that must be constrained. Among the quantities not directly accessible from observations are the radial velocity (and hence the full space velocity), the age and birthplace, the pre-supernova mass and radius of the binary orbit, and the asymmetry of the supernova explosion. The constraints on these parameters are interrelated and complex.

To clarify the situation, we begin by allowing the assumed radial velocity of the system to vary. We will find that assuming the system was born near the plane of the Galaxy (where most massive stars are found) in the last 210 Myr is sufficient to severely limit both the current space velocity of the pulsar and the kick velocity given to the binary system at birth. This systemic kick, the post-supernova eccentricity and size, and the misalignment all depend on the pre-supernova orbital size, the mass loss during the supernova, and the magnitude and direction of any asymmetric kick given to the companion.

We will show that the range of kick magnitudes and progenitor masses that satisfy all the constraints is very limited.

### 4.1. *The binary elements*

The relatively low eccentricity of the observed binary together with equation 4 constrains the size of the pre-supernova binary to within about 30%. Evolutionary arguments constrain the pre-supernova mass of the companion star to between about 2 and 5.5 solar masses. Precession studies constrain the post-explosion misalignment with the discrete a ambiguity between nearly aligned pulsar spin and orbital angular momenta ($\delta \sim 25°$) and nearly counteraligned angular momenta ($\delta \sim 155°$).

Given the observed orbital parameters for PSR B1534+12, we can rewrite equations 1–3 as

$$V_x = \pm 380\left[(\alpha - 0.785)(1.377 - \alpha)\right]^{1/2} \tag{11}$$

$$V_y = 395\left(\pm 0.872\alpha - \sqrt{\frac{\alpha}{\beta}}\right) \tag{12}$$

$$V_z = \pm 160\alpha \tag{13}$$

In equation 12, the + sign refers to the nearly aligned case, the − sign to the nearly counteraligned case.

From the observed parameters, we know that $0.785 \leq \alpha \leq 1.38$. With no assumptions about the mass loss in the second supernova explosion, this gives us direct constraints on two components of the kick velocity: $130 \leq |V_z| \leq 220$ km/s, and $|V_x| \leq 115$ km/sec.

The parameter $\beta$ is strictly less than one, reaching this limit only if no mass is lost in the second supernova. With the conservative assumption that the presupernova mass of the companion star was at least $2M_\odot$, we have $\beta \lesssim .8$. If the misalignment of the system is $\delta \sim 155°$, then a very large kick in the direction opposite to the instantaneous orbital motion is required, with $V_y < -620$ km/s for no mass loss and $V_y < -660$ km/s for a $2M_\odot$ presupernova mass. The minimum total kick speeds are 630 km/s and 670 km/s.

In the $\delta \sim 25°$ case, much smaller kicks are acceptable. For the no-mass-loss case the constraint is $-80 < V_y < 11$ km/s, with a minimum total kick speed of 149 km/s, for a $2M_\odot$ presupernova mass $-120 < V_y < -44$ km/s with a minimum total of 173 km/s.

Given the mass loss and natal kick, we can use equations 7 and 8 to calculate the systemic velocity kick acquired by the binary in the second supernova. In Fig. 2, we show the relationship between the pre-supernova properties of the binary and the components of this kick perpendicular and parallel to the post-explosion orbital plane. It is immediately evident that a natal kick large enough to leave $\delta \sim 155°$ inevitably leaves the binary system moving fast compared to the observed 122 km/s transverse velocity, suggesting that such large misalignments are only possible if the current binary velocity is fortuitously aligned very nearly along the line-of-sight to the pulsar. As we will see in the next section, such alignment is not consistent with our knowledge of the orientation of the binary.

### 4.2. *Motion of the binary in the Galaxy*

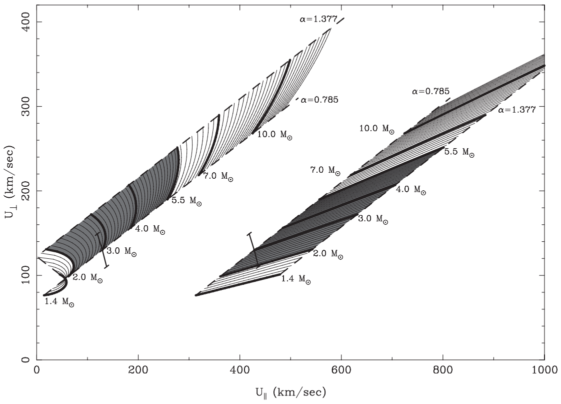


Fig. 2.— The center-of-mass (or "systemic") velocity imparted to the PSR B1534+12 binary at the time of the second supernova, broken into components perpendicular and parallel to the post-explosion orbital plane. The sign of $U_\perp$ is unconstrained. The shaded regions mark the initial states allowed by the presupernova binary evolution models of Dewi & Pols (2003). The "island" of points at relatively low velocity are the solutions with $\delta = 25°$, while the island at high velocity are solutions with $\delta = 155°$. Representative error bars show the effect of varying $\delta$ within the allowed $1\sigma$ range. Lines of constant presupernova mass are shown, as are lines of constant presupernova orbital size, as parameterized by $\alpha$ (see eq. 4).

The full three-dimensional orientation of the PSR B1534+12 orbit is known. The orbital inclination relative to the plane of the sky ($\sin i$) is known from timing measurements. The usual ambiguity in the sign of $\cos i$, which is not accessible from timing studies, is known from the profile observations. The angle of the line of nodes, corresponding to the rotation of the binary around the line of sight, is known from scintillation studies. Together, these observations fix the direction of the orbital angular momentum vector in space. Because tidal forces on the binary are very small, there has been no significant change in the direction of the angular momentum vector since the current binary was formed in the second supernova explosion.

The arguments of the last section give us, for any given presupernova parameters, the components of the systemic velocity kick parallel to and perpendicular to this angular momentum vector (e.g., Fig. 2). Ideally, we could compare those kick velocity components directly to the observed space motion of the binary, but we must first overcome two significant problems. First, although the transverse motion of the binary is well determined, there is no direct constraint on the radial velocity. Second, the current velocity has been substantially affected by acceleration of the binary as it moves in the Galactic gravitational potential.

Fortunately, the age of the binary is relatively low, so it is not unreasonable to follow its motion backwards to find possible birth locations and to thereby estimate the systemic kick at birth. It is very likely that the original pair of massive stars was born near the plane of the Galaxy, moving relatively slowly. The scale height of O type stars is small, ∼ 50 pc (Stone 1979), and their peculiar velocities are low. Even after the first supernova explosion, the space velocity remains low, comparable to the fractional mass loss times the presupernova orbital velocity. In the canonical evolutionary model, where conservative mass transfer prior to the first supernova leads to orbital widening (Bhattacharya & van den Heuvel 1991, for example), a typical velocity kick is $\sim 10 - 20$ km/s.

The velocity of the binary is therefore dominated by the recoil introduced in the second supernova explosion, when both the fractional mass loss and the pre-supernova orbital velocity are much higher than they were in the first explosion. The binary is currently far from the Galactic plane, at $z = 680$pc. Assuming the binary was moving with the local Galactic rotational velocity and was in the Galactic plane at the time of the second supernova will introduce only minor errors to estimates of the age and systemic kick velocity.

We have studied the motion of the pulsar through the Galaxy using the potential model of Kuijken & Gilmore (1989). A series of trial radial velocities was used. In each case, the solar motion was added to the pulsar motion to produce a space velocity. The orbit of the pulsar was then integrated backwards for 210 Myr. Each plane crossing represents a potential birth place and time for the binary system. Subtraction of the local rotational velocity then yields the systemic kick velocity needed at the time of the second supernova to carry the binary to its observed location. This can be decomposed into components parallel to and perpendicular to the post-supernova orbital plane, but we first discuss conclusions that are independent of the orientation of the system.

Depending on its age, birth location, and kick velocity, we find that the binary could be on its first, second, third, fourth, or even (with careful fine tuning) even fifth excursion away from the Galactic plane. If this is *not* the initial departure from the plane, then we find that any pulsar age between 70 and 210 Myr is possible, as is any current radial velocity between about $\pm 220$ km/s.

Radial velocities with $v_r \gtrsim 200$ km/s are only acceptable if it is still on its initial excursion away from the plane. A large velocity directed nearly radially away from us implies that the pulsar was born recently in the near neighborhood of the Sun. For example, $v_r = 200$ km/s implies an age of just 7.9 Myr, while $v_r = 300$ km/s implies an age of 4.5 Myr and a birth within a kiloparsec from the Sun. While we cannot rule out arbitrarily large radial velocities, they require a fortuitous viewing angle and we believe them to be highly unlikely for other reasons. First, the young implied ages require that the pulsar birth period was very close to the observed period, and well below the spin-up line. This requires very fine tuning of the accretion parameters during spin-up. Second, unless we were extraordinarily lucky to find a double neutron star system born so recently in the solar neighborhood, the implied birthrate would be extraordinarily high.

If the binary has a large radial velocity *towards* us, then it must be returning to the plane for the first time. Again, fortuitous viewing alignments are difficult to rule out. However, in this case the velocity is directed generally towards the Galactic center, so a radial velocity as high as $-300$ km/s implies a birthplace at a very large Galactocentric radius, $R > 15$ kpc. We regard birth at such large radii to be unlikely.

We conclude, therefore, that the radial velocity is almost certainly between $-300$ km/s and $+220$ km/s, and probably between $\pm 220$ km/s. We cannot set firm limits

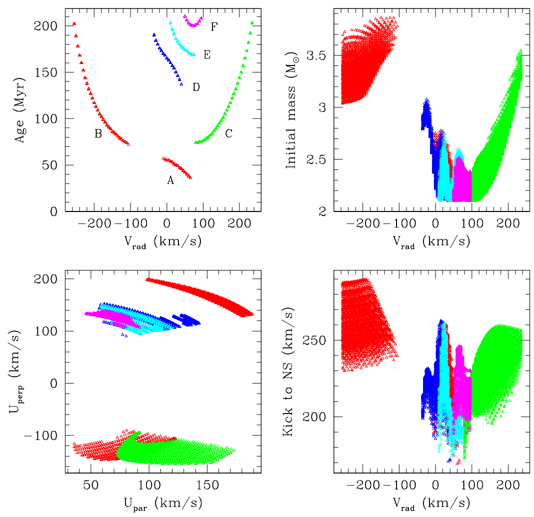


FIG. 3.— Possible histories of the PSR B1534+12 binary. For each possible radial velocity, the orbit in the Galaxy was integrated backwards, and each Galactic plane crossing was recorded. The necessary systemic kick components parallel to and perpendicular to the post-supernova orbit were calculated. Plotted solutions are those allowed for some choice of presupernova companion mass $m_{2i}$ and semimajor axis $a_i$, given $1\sigma$ ranges in the parameters $\delta$ and $\Omega$. Several families of acceptable solutions exist, marked by letters and summarized in Table 1. Top left: Possible ages of the binary system, assuming the binary was born near the Galactic plane. The lowest curve in this figure (red points in the electronic edition) includes possible histories where the binary is leaving the plane for the first time (positive radial velocities) or returning for the first time (negative radial velocities). The second curve (green in the electronic edition) describes solutions where the binary is leaving or returning to the plane for the second time, and so forth. For the smallest allowed orbits, there is time in 210 Myr for the pulsar to be on its fifth excursion from the plane (having started its third complete orbit in the Galactic potential). Top right: Allowed presupernova companion masses. Bottom left: Allowed systemic kick velocities, relative to the postsupernova orbital plane. This figure can be compared with Fig. 2. Note that there are no solutions consistent with $\delta \approx 155°$. Bottom right: Magnitude of the asymmetric velocity kick imparted to the companion star at the time of the second supernova explosion.

on the age of the system, but it is very likely more than about 100 Myr. Most important for our present purposes, we note that in all of the acceptable models the systemic kick given to the binary at birth was between $\sim 100$ and $\sim 240$ km/s.

Note that this conclusion is already strong enough to exclude the very large kicks needed to produce $\delta \sim 155°$. Also excluded are scenarios with large presupernova masses, such as those of Dewi & Pols (2003) that avoid a second period of Roche lobe overflow, since the minimum presupernova mass in these models, $\sim 4.5 M_\odot$, requires a minimum systemic kick of $\sim 270$ km/s. The only models consistent with the observed low velocities are the case BB models in which the second helium star explodes with a mass of $\sim 2 - 4 M_\odot$.

### 4.3. *Orientation of the orbit*

These constraints can be further tightened using our knowledge of the post-supernova orbital orientation. After propagating the binary back to a potential birthplace to find the direction and magnitude of the systemic kick that was needed at birth, we can resolve this

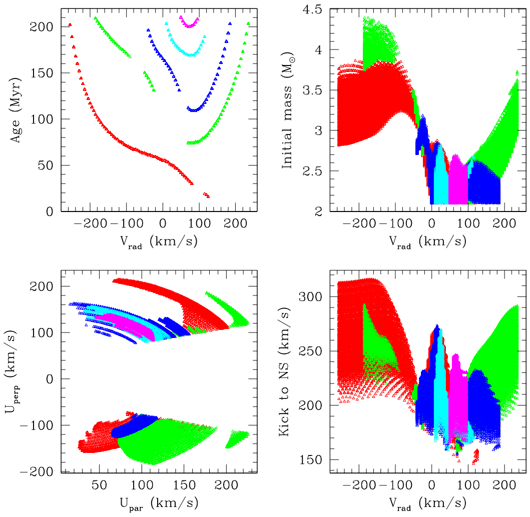

FIG. 4.— Identical to Fig. 3, except $2\sigma$ ranges in $\delta$ and $\Omega$ are accepted. The most important difference is that some second-pass solutions with larger negative radial velocity are allowed, somewhat broadening the range of allowed presupernova companion masses.

TABLE 1
POSSIBLE BIRTH PROPERTIES

| Key[a] | Pass[b] | Age[c] (Myr) | $m_{2i}$ ($M_\odot$) | $V_k$ (km/s) |
|---|---|---|---|---|
| A | 1 | 40–60 | 2.1–2.7 | 170–260 |
| B | 1 | 70–210 | 3.0–3.9 | 230–290 |
| C | 2 | 70–210 | 2.1–3.6 | 170–260 |
| D | 3 | 130–190 | 2.1–3.1 | 170–260 |
| E | 4 | 170–210 | 2.1–2.7 | 170–260 |
| F | 5 | 200–210 | 2.1–2.5 | 170–250 |

[a]See Fig. 3.
[b]Excursion from the Galactic plane. For example, pass 2 means that the binary has already returned to the plane once since receiving its large velocity kick during the second supernova.
[c]Time since second supernova explosion.

kick into components perpendicular and parallel to the post-supernova orbital plane and solve equations 5 and 7 for the presupernova orbital size and companion mass. Using Kepler's law to eliminate $a_i$, and some algebraic manipulation, we can rewrite equation 5 as a simple quadratic equation in $m_{2i}$:

$$0 = m_{2i}^2\left[u^2 - \frac{u_\perp^2}{\sin^2\delta} + \frac{Gm_{2f}^2}{(m_{2f}+m_1)a_f}\right] -2(m_{2i}+m_1)\left[\frac{m_{2f}^2}{m_{2f}+m_1}\frac{u_\perp^2}{\sin^2\delta} -m_{2f}\frac{u_\perp^3}{\sin^3\delta}\sqrt{\frac{a_f}{G(m_{2f}+m_1)}}\sqrt{1-e^2}\cos\delta\right] \quad (14)$$

Allowing for the sign ambiguity in $u_\perp$, there are up to four real roots, each with a corresponding $a_i$ that can be determined from Kepler's equation.

Physically interesting solutions have $m_{2i}$ in the range $2.1\,M_\odot$–$10\,M_\odot$ and $a_i$ within the range given by equation 4. We consider 1 and $2\sigma$ ranges in $\Omega$ and $\delta$ when computing the full set of possible progenitors. The resulting set of allowed solutions are shown in Figs. 3 and 4. We find viable solutions with 1–5 disk crossings and ages less than 210 Myr. There are no solutions with radial velocities less than $-260$ km/s or more than 240 km/s. The kick to the NS is relatively tightly constrained to between 170 and 290 km/s (between 150 km/s and 320 allowing for $2\sigma$ regions), while the progenitor mass cannot have been more than $\sim 3.8\,M_\odot$ ($4.4M_\odot$ for $2\sigma$ regions), again implying that only case BB progenitors are possible. The kick direction is oriented within roughly 20–40° or 140–160° of the pre-supernova orbital angular momentum (with the ambiguity again arising from the ambiguity in the sign of the perpendicular component of the velocity kick) and the component of the natal kick that is in the presupernova orbital plane is directed roughly opposite to the instantaneous progenitor motion at the time of explosion.

Several sources of uncertainty contribute to our results at a comparable level. Included in our analysis are the $\sim 20°$ uncertainty in $\Omega$, which introduces uncertainty in the decomposition of the birth velocity into parallel and perpendicular components, and the $\sim 4°$ uncertainty in $\delta$ (e.g., Fig. 2). A smaller contribution is the $10-20$ km/s uncertainty in the presupernova peculiar velocity of the binary.

Another significant uncertainty, particularly for solutions with high space velocity, is the Galactic potential model used to model the binary's motion from the Galactic plane. We have repeated our analysis of the binary space motion using the three component potential of Johnston et al. (1995), and find very similar results. The only significant difference is that for a very small range of radial velocities (between $-205$ and $-220$ km/s, on the second excursion from the Galactic plane, ages 200–210 Myr) there are models with more massive presupernova progenitors ($m_{2i}$ = 5–5.6$M_\odot$) that are consistent with the errors in $\Omega$ and $\delta$. We regard these scenarios as unlikely, requiring careful fine-tuning as well as less-commonly used potential model, but the difference does highlight the systematic uncertainties in following the orbit of such high-velocity objects in the Galaxy. (Those particular solutions are just returning to the plane from a maximum height of $\sim 6$ kpc.)

In summary, a number of error sources as well as discrete ambiguities in the age of the system make it impossible to precisely determine the parameters of the presupernova orbit, even with the available data on the orbital orientation. However, the data are sufficient to strongly constrain the parameters: it is, for example, likely that the progenitor mass was in the range $\sim 3 \pm 1M_\odot$, and that the natal kick is $\sim 230 \pm 60$ km/s.

## 5. CONCLUSIONS

The combination of timing, precession, and proper motion studies have allowed us to strongly constrain the evolution of the PSR B1534+12 binary. There are several conclusions that can be drawn:

1. The misalignment of the pulsar spin axis from the orbital angular momentum is relatively small, with $\delta = 25.0 \pm 3.8°$. Although a misalignment of $155.0 \pm 3.8°$ was formally allowed by observations of geodetic precession in the system, such a large misalignment would require an asymmetric kick at the

time of the second supernova explosion that is too large to reconcile with the current space velocity of the binary.

2. Of the evolutionary scenarios studied by Dewi & Pols (2003), only one is consistent with the observed properties and space velocity of the binary. The pulsar was the first-born neutron star of the pair. After an initial inspiral during either case B or C mass transfer as its companion evolved off the main sequence, the companion was a helium star between about 3.3 and $6.5M_{\odot}$. A second phase of mass transfer (case BB) left the companion with mass $3 \pm 1M_{\odot}$ at the time of the second supernova explosion. Models that avoid a second phase of Roche-lobe-overflow-driven mass transfer in the binary by positing a high zero age helium main sequence mass for the companion also require an asymmetric kick that is too high.

3. In the second supernova explosion, an asymmetric kick of $230 \pm 60$ km/s was required to produce the observed orbital elements. The direction of the kick relative to the orbital angular momentum vector (and presumably the angular momentum of the presupernova core) is tightly constrained, and is not obviously biased towards either the pole or the orbital plane. We note that the inferred asymmetric kick is somewhat larger than the 100-150 km/s most-likely kick for PSR J0737−3039, estimated from scintillation (Ransom et al. 2004) and evolutionary arguments (Willems & Kalogera 2004), and probably somewhat smaller than the kick given to the companion of PSR B1913+16, which is poorly constrained. An early analysis found most likely solutions for PSR B1913+16 to be $\sim 300 - 500$ km/s (Wex et al. 2000, prograde solution), but the range expands to 190–600 km/s when evolutionary scenarios including Roche lobe overflow are included (Willems et al. 2004). The limited measurement quality and complex selection biases make it impossible to estimate the distribution of kick velocities imparted to newborn neutron stars in close binaries, but we note that there is no significant evidence in this small sample for a different velocity distribution.

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