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CONSTRAINTS ON THE PROGENITOR BINARY SYSTEM FOR PSR 1913+16

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ABSTRACT

We examine constraints on the configuration of the presupernova progenitor of the binary pulsar system using limits on the proper motion of PSR 1913+16. The sensitivity of pulse shape data to geodetic precession of the pulsar spin axis is studied in an effort to limit explosion asymmetries perpendicular to the orbital plane of the progenitor. We find that all alignment of spin axis and orbital angular momentum is not yet demanded by observations. Observations which should narrow the allowed range of presupernova masses and radii are discussed.

Subject headings: pulsars — stars: binaries — stars: individual

I. INTRODUCTION

Most radio pulsars are isolated objects with large space velocities, large enough in some cases to escape the Galaxy (Lyne 1981). In spite of the fact that multiple star systems abound in the Galaxy, relatively few ($\sim 1\%$) of the radio pulsars are found in binary star systems. Although it may be difficult to account for the nonnegligible number of pulsars that have *small* space velocities, the paucity of binary radio pulsars lends support to pulsar-forming scenarios in which binary star systems are disrupted by supernova explosions. In such scenarios, however, it is not clear that the resulting pulsar space velocity derives *solely* from the pre-explosion orbital motion of the disrupted binary. Asymmetric magnetic dipole radiation (Harrison and Tademaru 1975), or asymmetric "kicks" associated with the pulsar-forming supernova event (cf. Flannery and van den Heuvel 1975; de Loore, de Greve, and de Cuyper 1975; Hills 1983), may also contribute significantly to the present-day translational motion.

In this paper we examine the binary pulsar PSR 1913+16 in detail in order to constrain the nature of the binary system before the last supernova. This binary seems to be "the exception that proves the rule" of formation of high-velocity *single* pulsars from supernovae in *multiple* star systems: its large orbital eccentricity ($e = 0.615$) implies that this binary, too, was almost disrupted.

It has been argued (Flannery and van den Heuvel 1975; Smarr and Blandford 1976) that, in its last previous evolutionary phase, the binary pulsar system consisted of a neutron star (the presently observed pulsar) and a massive helium star (3–10 $M_\odot$) in an orbit comparable in size to the present one. In this picture the explosion of the helium star (resulting in the unseen companion of PSR 1913+16) was preceded by a phase in which the present-day radio pulsar was an accreting X-ray source. During this stage, the spin period of PSR 1913+16 decreased significantly as a result of accretion torques, and its magnetic field may also have decayed appreciably. Assuming no significant postexplosion evolution of the orbit, previous authors (Flannery and van den Heuvel 1975; de Loore, de Greve, and de Cuyper 1975; de Cuyper 1981; Hills 1983) have discussed the possible ranges of presupernova masses and orbital radius of the system. The set of equations is underdetermined, however, so one must introduce additional constraints, such as the probability of disruption for asymmetric kicks with no *a priori* favored direction (de Cuyper 1981; Hills 1983).

Here, we take a different approach that uses observational limits on the proper motion of the binary system to further narrow the allowed range of progenitor binary systems. We outline the dynamical assumptions underlying our derived constraints in § II. Most importantly, we restrict asymmetric kicks, owing to explosion anisotropies, to lie entirely in the orbital plane of the progenitor system. In § III we demonstrate that while this assumption is *consistent* with the observed stability of the pulse shape of PSR 1913+16 it is *not* (*yet*) *required* by it. The allowed presupernova systems, corresponding to various present-day proper motions, are determined in § IV. We give observational limits on the proper motion in § V. A summary of results and conclusions is given in § VI.

II. ASSUMPTIONS

We assume that the present-day binary system consists of a neutron star (m_1), PSR 1913+16, and an unobserved companion (m_2) that is probably a neutron star but possibly a black hole. The components are taken to be equally massive, which is consistent with the observational values $m_1 \approx m_2 \approx (1.4 \pm 0.1)\ M_\odot$ determined by Taylor and Weisberg (1982) from a post-Newtonian, general relativistic analysis of the timing data. We assume that the angular momentum and total energy of the binary orbit have remained essentially unchanged since the last supernova explosion in the system. Although gravitational radiation is apparently decreasing the orbital period with a characteristic time $|P_b/\dot{P}_b| \approx 10^{8.6}$ years, the elapsed time since the last supernova should be much shorter. To reach its present altitude above the galactic plane, $h \sim 200$ pc, the binary could have been moving with a velocity $v \sim 100$–1000 km s^{-1} for only $\sim 10^6$–10^7 years.

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Since the binary pulsar system contains two collapsed stars, it seems reasonable to suppose that it has been the site of two supernovae. We assume that PSR 1913+16 was formed in the first supernova and was spun up to $P \approx 59$ ms during one or more episodes of mass transfer. The spin axis of the neutron star should therefore have been parallel to the orbital angular momentum of the binary just prior to the explosion of the companion star. The progenitor binary system presumably also had a very nearly circular orbit as a result of mass transfer and tidal torques. (See also Flannery and van den Heuvel 1975; de Loore, de Greve, and de Cuyper 1975; Smarr and Blandford 1976; de Cuyper 1981; and Hills 1983.)

The net effect of the second supernova is assumed to be instantaneous mass loss, and with it, associated changes in the angular momentum, total energy, and total momentum of the binary. We ignore the effects of ablation, as seems reasonable since the cross-sectional area of the neutron star is small (de Cuyper 1981). We also assume that any asymmetric kicks due to anisotropies of the explosion are parallel to the orbital plane of the binary. We discuss this assumption in more detail below.

III. ASYMMETRIC KICKS OUT OF THE ORBITAL PLANE

In general, the asymmetric kick suffered by a binary star system in which an anisotropic supernova has occurred can point in any direction (see, e.g., Hills 1983). If, however, the spin axis of the collapsing star is parallel to the orbital angular momentum of the binary, the explosion dynamics should be symmetric about the orbital plane, barring any strong "symmetry-breaking" effects due to non-aligned magnetic fields. It seems not implausible, therefore, that any explosion anisotropies are strictly confined to the orbital plane.

Non-coplanar kicks, if large ($\Delta V_{\rm kick} \sim V_{\rm orbital}$), can exert substantial torques on the binary, so that the pre- and post-explosion orbital angular momenta of the system are not parallel to one another. If, as we have assumed, the spin axis of PSR 1913+16 was parallel to the orbital angular momentum of the *progenitor* binary, then non-coplanar kicks would result in *considerable misalignment* of the pulsar spin and orbital angular momentum in the *present-day* binary pulsar system.

Taylor and Weisberg (1982) have argued qualitatively that the spin vector $\boldsymbol{S}$ and orbital angular momentum $\boldsymbol{J}$ must be very nearly parallel to one another. The gist of their argument is that if $\boldsymbol{J} \times \boldsymbol{S} \neq 0$, then geodetic precession of $\boldsymbol{S}$ about $\boldsymbol{J}$ would cause observable changes in the pulse shape of PSR 1913+16 over several years time. Quantitatively, as a result of geodetic precession

$$\Delta \hat{S} = \Omega_p \hat{J} \times \hat{S} P_{\rm orb} \tag{1}$$

is the average change of $\hat{S} \equiv \boldsymbol{S}/|\boldsymbol{S}|$ per orbit, with $\hat{J} \equiv \boldsymbol{J}/|\boldsymbol{J}|$ and

$$\Omega_p = \frac{3\pi G m_2 (1 + m_1/3M)}{a c^2 (1 - e^2) P_{\rm orb}} , \tag{2}$$

where a is the semimajor axis and $M \equiv m_1 + m_2$. The "characteristic" precession rate, if $\boldsymbol{J}$ and $\boldsymbol{S}$ are randomly oriented, is

$$\Omega_p P_{\rm orb} = 1.88 \times 10^{-5} \text{ rad/orbit} = 1.22 \text{ deg/year} \tag{3}$$

using orbital elements given by Taylor and Weisberg (1982). Thus, it would appear that unless $\boldsymbol{J} \times \boldsymbol{S} \approx 0$, a few degrees of geodetic precession would have accumulated over the several years of accurate data now available for the binary pulsar. Several percent changes in the pulse shape of PSR 1913+16 would *seem* to be required if this much precession has occurred. The apparent absence of symmetric pulse shape evolution thus appears to rule out any substantial misalignment of $\boldsymbol{J}$ and $\boldsymbol{S}$ in the present-day binary pulsar system, and with it, any large non-coplanar kicks due to the last supernova.

The pulse shape data are, of course, consistent with $\boldsymbol{J} \times \boldsymbol{S} = 0$ and the absence of non-coplanar supernova asymmetries. To determine whether or not the pulse shape data *require* $\boldsymbol{J} \times \boldsymbol{S} = 0$ we need to make some assumptions about the pulsar beam detected by an observer, taken to be in the direction $\hat{n}$ from the pulsar. We presume that the beam pattern is an even function in angle about the unit vector $\hat{\mu}$ along the magnetic axis of the pulsar, whose colatitude is fixed relative to $\hat{S}$. At the pulse midpoint, $\hat{n}$, $\hat{S}$, and $\hat{\mu}$ are coplanar, and the pulse shape, duty cycle, and polarization angle gradient along the pulse are consistent with $1 - \hat{n} \cdot \hat{\mu} \ll 1$ at that instant.

Now let α be the angle between $\hat{n}$ and $\hat{\mu}$ at the moment when $\hat{n}$, $\hat{S}$, and $\hat{\mu}$ are coplanar. Then α, which may be either positive or negative, is the (fixed) magnetic latitude at which the observer's line of sight sweeps across the pulsar beam. Assuming the beam to consist of core and cone components only (Backer 1976; Rankin 1983), the pulse shape at any frequency should contain two or perhaps three components. PSR 1913+16 shows both the core and cone components of the beam at 0.43 GHz, suggesting that α at present is much smaller than the beam width. Only the cone component appears at 1.4 GHz, the frequency at which the most precise timing measurements have been made, so we will model only the hollow cone part of the beam.

Let $\theta_{\rm sep}$ be the observed separation of the (twin) pulse peaks. If the beam pattern is an even function in α (but not necessarily azimuthally symmetric), then

$$\theta_{\rm sep} = f(\alpha^2) ; \tag{4}$$

and for small $\alpha \ll 1$, in general,

$$\theta_{\rm sep} = \theta_{\rm sep}(0) + \frac{\lambda \alpha^2}{2\theta_{\rm sep}(0)} + \ldots , \tag{5}$$

where $\lambda \sim 1$. If α changes from 0 to $\delta\alpha$ over some reasonably long observing period, $t \sim$ years, then

$$|\delta\alpha| = \frac{\theta_{\rm sep}(0)}{(\lambda/2)^{1/2}} \left| \frac{\delta\theta_{\rm sep}}{\theta_{\rm sep}(0)} \right|^{1/2} , \tag{6}$$

where $\delta\theta_{\rm sep} \equiv \theta_{\rm sep} - \theta_{\rm sep}(0)$. Observations at 1.4 GHz in 1977 (Fowler, Cordes, and Taylor 1979), 1978 (Fowler 1979), and 1981 (Taylor and Weisberg 1982; Boriakoff *et al.* 1982) imply $\theta_{\rm sep} = 39.0 \pm 0.1$. Taking $|\delta\theta_{\rm sep}/\theta_{\rm sep}(0)| \lesssim 10^{-2}$ as a conservative limit for this 4-year observing period, we get

$$|\delta\alpha| \lesssim \frac{5.5}{\lambda^{1/2}} \left| \frac{\delta\theta_{\rm sep}/\theta_{\rm sep}(0)}{10^{-2}} \right|^{1/2} \text{deg} . \tag{7}$$

In the elliptical beam models of Narayan and Vivekenand (1983) $\lambda = 1/\zeta^2$, where $\zeta \approx 3$ for typical pulsars, and therefore $|\delta\alpha| \lesssim 16^\circ\!.5$. By comparison, from equation (1) we find, after some trigonometry,

$$\Delta\alpha = \Omega_p P_{\rm orb} \cos\eta \sin i \tag{8}$$

per orbit, so that over a 4-year time span

$$\delta\alpha = 3.5 \cos \eta \text{ deg}\ , \tag{9}$$

where η is defined by

$$\sin i \cos \eta = \frac{\hat{n} \cdot (\hat{S} \times \hat{J})}{[1 - (\hat{n} \cdot \hat{S})^2]^{1/2}} \tag{10}$$

and i is the inclination angle of the orbit (cf. Smarr and Blandford 1976, Fig. 1 and eq. [2.11]). From equation (9) we see that $|\delta\alpha| < 3^\circ\!.5$ due to geodetic precession, so that the observational bounds, equation (7), cannot yet rule out the possibility that geodetic precession is occurring. Thus, *the pulse shape data do not require* $\boldsymbol{J} \times \boldsymbol{S} = 0$.

The insensitivity of $\theta_{\rm sep}$ to changes in α results from the circumstance that α is near 0 today. As α increases, observable changes in the pulse shape should occur relatively rapidly, with $\delta\theta_{\rm sep}/\theta_{\rm sep} \sim \alpha\delta\alpha/\theta_{\rm sep}^2$. Thus, for example, $\delta\theta_{\rm sep}/\theta_{\rm sep} \sim 10^{-2}$ should arise in $t \lesssim (\cos \eta)^{-1}$ years once $\alpha \gtrsim 10^\circ$. Data on polarization gradients across the pulse may already be sensitive to the first power of $\delta\alpha$, and could provide the most useful probe for geodetic precession in the binary pulsar system (cf. Smarr and Blandford 1976). Of course, the fact that α is near 0 at present could be taken as indirect evidence that geodetic precession is negligible, since if $\alpha \approx 0$ but $\eta \neq \pi/2$ then it could be argued that we live at a rather special time for observing this unusual binary pulsar system.

IV. POSSIBLE PROGENITOR SYSTEMS

By confining asymmetries to the orbital plane and using energy and angular momentum conservation in the context of the assumptions given in § II, we solve for the parameters of the presupernova orbit in terms of the present orbital parameters and present translational velocity of the binary. The results are

$$\frac{a}{r'} = \frac{1 \pm [e^2 - (1 - e^2)(M/m_1)^2 V_\perp{}^2/(GM/a)]^{1/2}}{1 - e^2} \tag{11}$$

and

$$(M'/M)^{1/2} = \tfrac{1}{2}[Q_\pm + (Q_\pm{}^2 + 4m_2/M)^{1/2}] \tag{12}$$

where

$$Q_\pm \equiv -(r'/a)^{1/2}[V_\parallel/(GM/a)^{1/2} \mp am_1(1 - e^2)^{1/2}/r'M]\ . \tag{13}$$

Primed (unprimed) quantities refer to the presupernova (present-day) system, $M \equiv m_1 + m_2$, e is the eccentricity, and $V_\parallel$ and $V_\perp$ are the translational velocity components with respect to the original center of mass of the presupernova binary, parallel and perpendicular to the instantaneous orbital velocity of the exploding star, respectively.

For each value of a/r' there are at most two solutions with $M'/M \geq 1$. In Figure 1 we show the *largest* allowed value of M'/M for each r'/a, for a variety of translational speeds V. Below $V = 171.1$ km s^{-1} real solutions with $M'/M > 1$ do not exist for every value of r'/a. The filled circles on the M'–r' limiting curves for $V = 100$ km s^{-1} and $V = 150$ km s^{-1} indicate these termination points.

V. OBSERVATIONAL LIMITS ON THE PROPER MOTION OF THE BINARY PULSAR

a) Limits for Existing Data

No estimates or limits on the proper motion based on pulse timing or interferometric observations exist in the literature. However, a tentative limit can be placed by using the timing data reported by Taylor and Weisberg (1982). Proper motion introduces into the times of arrival a sinusoidal term with

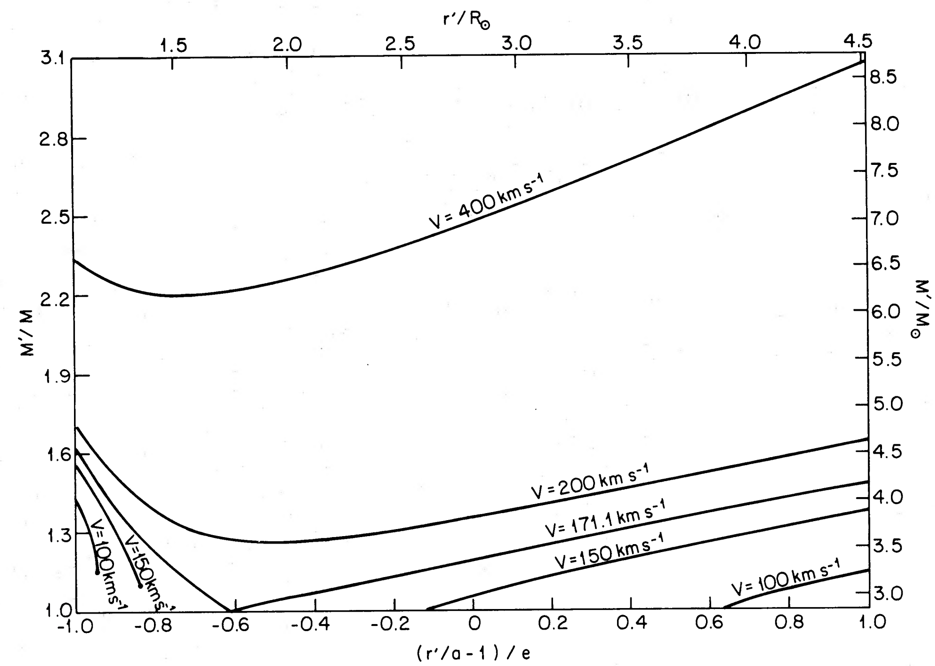

FIG. 1.—The total mass of the binary before the last supernova (M') is plotted against the orbital radius (r') for different values of the present day space velocity. Only the largest allowed value of M'/M is shown for each value of r'/a. The present day mass, semimajor axis, and eccentricity are M, a, and e, respectively.

1-year period that grows linearly with time if no proper motion is explicitly accounted for (Manchester and Taylor 1977, p. 105). For PSR 1913+16 this implies an rms time-of-arrival error $\sigma_R \approx 3.1 V_{100} T_{yr}$ μs, where V_{100} is the transverse velocity in units of 100 km s^{-1}, assumed to be equally divided in orthogonal components in the right ascension and declination directions; T_{yr} is the observing time in years. Since the rms error in time of arrival, σ_{TOA}, has decreased by more than a factor of 10 in measurements from 1974 to 1981, there is a tradeoff between using only the most recent data and choosing a large enough T_{yr} to derive the strongest limit. By including data from 1978 to 1981, we conclude that a safe limit on any transverse velocity is

$$V < 200 \text{ km s}^{-1} \tag{14}$$

because the corresponding time-of-arrival error over 3 years, ~ 20 μs, is within the limits of the distribution of postfit residuals for fits that do not include proper motion. Note that tests for statistical independence of postfit residuals, which show independence down to the 5 μs level (Taylor and Weisberg 1982; Boriakoff *et al.* 1982), have been performed only on residuals of data obtained since 1981 and therefore do not yet constrain the proper motion.

A transverse velocity of 200 km s^{-1} corresponds to a proper motion $\dot{\theta} = 8$ milliarcsec yr^{-1}, so a 3-year duration implies a total position change somewhat less than the range of positions derived from fits to subsets of time of arrival data reported by Taylor and Weisberg (1982). The total time span of available data, ~ 6.5 yr, cannot be used to constrain $\dot{\theta}$ because phase offsets used to refer data from different observing systems to the same time origin remove some or most of any proper motion contribution to the times of arrival.

b) Prospects for Measuring the Proper Motion

It is clear that continued time-of-arrival measurements over several years (with a constant time origin) will lead to a determination of the proper motion. Whereas timing determinations of proper motions of some other pulsars have been controversial, mainly because of intrinsic rotation fluctuations that cannot be adequately modeled, the binary pulsar should allow a clean fit because there is very little such "timing noise." VLBI techniques do not appear promising because the pulsar is weak (1 mJy effective average flux density at 21 cm) and has a steep spectrum. Observations will therefore be restricted to $\lambda \gtrsim 21$ cm for which ionospheric and interstellar scattering effects will degrade VLBI calibrations.

The most promising technique involves measurements of interstellar scintillations of the pulsar. Lyne and Smith (1982) have recently shown that interferometrically determined proper-motion velocities correlate at the 66% level with transverse speeds determined from scintillation bandwidths and fade times. Unknown geometric factors (such as the precise distribution of scattering material along the line of sight) cause the scintillation speed to be only of statistical interest in a large sample of non-binary pulsars. A binary pulsar, however, allows a calibration of the scintillation speed with the known orbital velocity. The proper motion can therefore be determined as the offset velocity of a linear relationship between measured scintillation speed and known transverse orbital velocity. PSR 1913+16 is sufficiently intense that a scintillation speed can be determined every 10 minutes (at Arecibo Observatory at 21 cm), yielding about 50 measurements per orbit. The accuracy of the proper motion determined with the scintillation technique is limited mostly by the differential galactic rotation and peculiar velocities of scattering material. A reasonable estimate of the uncertainty is ± 20 km s^{-1}.

VI. SUMMARY AND CONCLUSIONS

Observational constraints on the nature of the progenitor of the binary pulsar system provide important experimental input to the theory of binary star evolution, and could possibly provide a rough determination of the mass of a pre-supernova star. Measurements of the proper motion of PSR 1913+16 would appear to be the most promising way to put limits on the pre-explosion orbital dynamics of the predecessor of the binary pulsar system.

The use of data on the proper motion of the binary pulsar system to constrain the mass M' and orbital radius r' of its binary progenitor is complicated by two sources of uncertainty. First, the measurement of the proper motion gives no information on the line-of-sight velocity of the binary, so that its *total* translational velocity remains undetermined. Second, if, as we have assumed, the binary pulsar system has been the site of *two* supernovae, then its present translational motion is the vector sum of two distinct momentum kicks associated with the explosion of each member of the binary. While we cannot rule out the possibility that the first supernova contributed significantly to present-day translational motion, it is likely that it occurred when the mass of the system was much greater than just prior to the second explosion, (e.g., Flannery and van den Heuvel 1975) and therefore gave a relatively small impulse to the binary. Barring any fortuitous circumstances (e.g., V entirely parallel or perpendicular to the plane of the sky), we can roughly accomodate these uncertainties by multiplying any limits on the proper motion of the binary pulsar system by a factor of 2. More accurately one might try to use the proper motion data to ascribe probabilities to various regions in the mass-radius phase space for possible progenitor binaries. We do not attempt to do this here.

For $V \lesssim 400$ km s^{-1} it is already apparent from Figure 1 that $M' \lesssim 8.7$ $M_\odot$ for the progenitor binary. A factor of 2 improvement on the upper bound, equation (14), on the proper motion (cf. § V*b*) would imply $M' \lesssim 4.8$ $M_\odot$. We note in passing that even for relatively low values of V, the implied constraints on M' and r' are not inconsistent with the mass-radius relation for helium stars derived by Paczyński (1971). However, for very low translational velocities, $V < 150$ km s^{-1}, the allowed values of M' are rather low. Whether or not supernovae in low-mass helium stars leave behind a stellar (neutron star) remnant if they can occur at all is, as yet, a matter of speculation.

As was discussed in §§ II and III, the most important simplifying assumption we have made in generating the curves shown in Figure 1 is that asymmetric kicks associated with explosion anisotropies are confined to the orbital plane of the progenitor binary. Non-coplanar kicks would cause the pulsar spin axis and present orbital angular momentum vector to be misaligned, thereby allowing considerable geodetic precession which, one might have hoped, would manifest itself observationally in detectable changes in the pulse shape of PSR 1913+16. Unfortunately, as we have shown in § III, the pulse shape is apparently relatively insensitive to changes in the orientation of the pulsar spin axis at present. Further study of the pulse shape and of polarization gradients across the pulse are required before substantial present-day geodetic precession and, consequently, non-coplanar explosion anisotropies can be ruled out. We will treat these issues in a subsequent paper.

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