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OPTICAL STUDIES OF MILLISECOND PULSAR COMPANIONS

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ABSTRACT

In observations of four binary millisecond pulsars with the Palomar 200 inch (5.1 m) telescope, we have detected white dwarf companions to PSR J1640+2224 and PSR J2145−0750 and placed upper limits of $m_r = 24$ and $m_r = 25$ on companions to PSR J0751+1807 and PSR J2229+2643. The temperature inferred for the companion to PSR J1640+2224 is $T = 3700 \pm 300$ K. The luminosity inferred for a star at a distance of 1.2 kpc is consistent with that expected from a $(2 \pm 1) \times 10^9$ yr old helium white dwarf. For PSR J2145−0750, the measured colors are inconsistent, possibly due to a combination of emission lines in the spectrum and systematic effects introduced when subtracting a nearby star. The companion temperature derived lies in the range 4300–6800 K. For a carbon-oxygen white dwarf, the corresponding cooling age is 2–6 $\times 10^9$ yr. The cooling ages of both systems with detected white dwarf companions are significantly less than the upper limits from the pulsar spin-down ages. For both pulsars, the inferred accretion rate for mass transfer during Roche lobe overflow is 2 orders of magnitude below Eddington accretion rates.

Subject headings: binaries: general — pulsars: individual (PSR J1640+2224, PSR J2145−0750) — stars: evolution — stars: fundamental parameters (temperatures) — white dwarfs

1. INTRODUCTION

In the past 3 years, the number of known binary millisecond pulsars (MSPs) in the Galactic disk has grown from eight to more than 25 (Taylor, Manchester, & Lyne 1993; Taylor et al. 1995). The overwhelming majority of binary MSPs are believed to have white dwarf (WD) companions, but only three WD/pulsar systems had been detected optically prior to this study, two of which actually contain slowly spinning pulsars (Kulkarni 1986; Bell, Bailes, & Bessell 1993; Bailyn 1993; Danziger, Baade, & Della Valle 1993). The ages of these systems, typically greater than 10^9 yr, combined with their distances (~1 kpc), make most of them faint even for the most powerful telescopes ($m_V \sim 24$–27). Yet optical studies of WD companions to neutron stars are crucial to our understanding of the evolution of binary pulsar systems. Constraints placed on the ages, masses, and proper motions by optical observations test the magnetic field decay timescale of neutron stars, cooling models for WDs, dynamics of the system in the Roche lobe overflow or common-envelope phase preceding the current epoch, and even equations of state for bulk nuclear matter.

Multicolor optical observations of binary pulsar companions provide important clues about the evolutionary history of these systems. The temperature, derived from the colors, places limits on the age of the system based on WD cooling models (Iben & Tutukov 1986; Koester & Schonberner 1986; Kapranidis 1985). For all companions detected prior to 1995 (PSR J0437−4715, PSR B0655+64, and PSR B0820+02), the cooling age agrees with the spin-down age within a factor of 2 (Bell et al. 1993; Danziger et al. 1993; Koester, Chanmugam, & Reimers 1992; Kulkarni 1986). However, even the oldest of these, PSR J0437−4715, at about 2×10^9 yr cooling time, is young compared with the ages of the oldest MSPs, which approach the age of the Galaxy. With a well-constrained distance, accurate photometry can be used to determine the radius and, hence, the mass of the WD. The deduced mass can be compared with the predicted mass for a WD that collapsed from a Roche lobe–filling helium core of the progenitor giant star (Savonije 1987; Joss, Rappaport, & Lewis 1987; Rappaport et al. 1995).

In § 2 we describe source selection, the observations completed, and astrometric measurements made. We tabulate the photometry for the stars found and give upper limits for the nondetections in § 3. For each system, we discuss how well our observations match expectations based on evolutionary models. Finally, in § 4 we apply our results to issues of pulsar population, initial spin periods, mass accretion rates, and WD cooling.

2. OBSERVATIONS

Four binary pulsars were selected for optical observations, primarily on the basis of their distance d, estimated from dispersion measure (Taylor & Cordes 1993), and their Galactic latitude b. Table 1 lists the pulsar and orbital parameters for each system obtained from pulse-timing measurements. The characteristic spin-down time, $\tau_c = P/(2\dot{P})$, is an upper limit on the age of the system, equal to the time for magnetic dipole braking from an initial spin period P_i much less than the current period P. The companion mass, $m_c(i = 60°)$, is estimated from the Keplerian mass function, assuming a pulsar mass of 1.4 $M_\odot$ and an orbital inclination angle of $i = 60°$. The helium core mass, m_c(Roche), is determined from the current orbital parameters of the system, assuming stable mass transfer during the entire Roche lobe–filling phase of the progenitor of the current system (Savonije 1987; Joss et al. 1987; Rappaport et al. 1995). For PSR J2145−0750, an attempt to calculate m_c(Roche) gives a meaningless number. The orbit is

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TABLE 1

PULSAR, COMPANION, AND ORBITAL PARAMETERS

Pulsar	b	d (kpc)	τ_c (10^9 yr)	P (ms)	P_b (days)	$m_c(i = 60°)$ ($M_\odot$)	m_c(Roche) ($M_\odot$)	Reference
J0751+1807......	+21°	2.0	8	3.5	0.26	0.15	0.12	1
J1640+2224......	+38	1.2	>20	3.2	175	0.30	0.31	2
J2145−0750......	−42	0.5	9	16.1	6.8	0.51	···	3
J2229+2643......	−26	1.4	25	3.0	93	0.15	0.30	4

REFERENCES.—(1) Lundgren et al. 1995; (2) Foster et al. 1995; (3) Bailes et al. 1994; (4) Camilo 1995.

too small to have contained the progenitor of any WD consistent with the mass function ($m_c > 0.43\ M_\odot$).

The observations were made on 1994 January 2 and 1994 July 8–11 using, respectively, the 4-Shooter (Gunn et al. 1987) and the Carnegie Observatories Spectroscopic Multislit and Imaging Camera (COSMIC) CCD cameras at the Palomar 200 inch (5.1 m) telescope. Table 2 indicates the total integration time and seeing conditions for each filter on each pulsar field. The filters used were g, r, and i in the Gunn photometric system (Thuan & Gunn 1976) and B in the Johnson system. Photometric data reduction was done using the PHOT and DAOPHOT packages in IRAF (Stetson, Davis, & Crabtree 1990).

In observations of four pulsars, two candidate WD companions were detected. Astrometry was performed using the *Hubble Space Telescope* guide stars (*HST* GSs) found in the field of each exposure. No assumptions about the orientation or pixel scale of the chip were necessary, since at least three guide stars were used in each image. Since the guide stars are substantially oversaturated in our deep images, their positions can only be measured to within ~1″ on the CCD. Combined with the 0″.5 systematic errors in the positions quoted in the *HST* GS catalog, the astrometry only gives the pulsar position to within ~1″. Figure 1 (Plate L4) displays representative images of the candidate pulsar companions. The positions of the stars in the J2000 equinox, ($16^h40^m16^s.78$, +22°24′09″.6) and ($21^h45^m50^s.46$, −07°50′18″.4), are 0″.8 (Foster et al. 1995) and 0″.2 (Bell et al. 1995) from the pulsar timing positions, within the astrometric uncertainty.

3. RESULTS

Table 3 presents multicolor photometry for the two pulsar companions observed. Photometric corrections were applied for atmospheric extinction and reddening. Extinction at Palomar (Hayes & Latham 1975) at the air mass of the observations is comparable to the statistical errors for these faint sources ($k_g = -0.179$ and $k_{g-r} = -0.093$). Since all of our sources are at high latitude, reddening (E_{B-V}) was found to be an insignificant effect using the reddening model of Burstein & Heiles (1982). The distance modulus is calculated using the Taylor & Cordes (1993) model for the interstellar electron density. The 25% uncertainty in distance derives from uncertainty in the electron density model.

In order to compare our magnitude measurements with WD temperature calibrations in the literature, we transformed from the Gunn to the Johnson system following Kent (1985) and Jorgensen (1994). Table 3 presents the measured magnitudes, m_B, m_g, m_r, and m_i (or upper limits), and the transformed values in the Johnson system, m_V^* and m_R^*. The color $B - V$ is given both by using the measured $m_B(B - V^*)$ and by transforming $g - r[(B - V)^*]$. The effective temperatures in Table 3 are based on the calibration of $B - V$ and $V - R$ colors by Bessell (1979).

We converted the measured magnitudes to absolute magnitudes using the distance modulus and the bolometric corrections of Lang (1980). The temperatures and luminosities reflect the ages and masses of the WDs in the context of cooling models. For typical MSP magnetic fields, irradiation of the WD by the pulsar is comparable to the cooling luminosity only in systems with $P_b < 1$ day and $P < 5$ ms (Tavani 1992), and only if the pulsar beam intersects the WD.

PSR J0751+1807.—This system consists of a 3.5 ms pulsar in a 6 hr orbit with a ~0.15 $M_\odot$ companion (Lundgren, Zepka, & Cordes 1995). An 8×10^9 yr old 0.3 $M_\odot$ helium WD has a cooling luminosity of $10^{-4.0}\ L_\odot$ (Iben & Tutukov 1986). A simple model (Mestel 1952) suggests luminosity scales linearly with mass for WDs of a given age, giving $L \sim 10^{-4.3}\ L_\odot$. The orbital and spin parameters of PSR J0751+1807 fall in the range where irradiation of the WD by the pulsar may be significant. Assuming a majority of the pulsar spin-down energy intercepted by the WD is thermalized and reemitted at the surface, we have, for the luminosity irradiating the companion,

$$L/L_\odot = 2.6 \times 10^{-5} \dot{P}_{-20} P_{\rm ms}^{-3} I_{45} (r_9/a_{12})^2, \quad (1)$$

TABLE 2

OBSERVATIONS: INTEGRATION TIMES (s)/SEEING (arcsec)

Filter	J0751+1807[a]	J1640+2224[b]	J2145−0750[b]	J2229+2643[b]
B	···	1800/1.3	600/1.8	···
g	900/1.5	1800/1.3	600/1.5	1800/1.5
r	900/1.5	1800/1.3	1200/1.8	1800/1.8
i	900/1.5	···	···	···

[a] 4-Shooter CCD chip 2.

[b] COSMIC CCD camera with reimaging optics.

TABLE 3

PHOTOMETRY[a]

Parameter	J0751+1807	J1640+2224	J2145−0750	J2229+2643
m_B	···	>24.9	24.5 (1)	···
m_g............	>23.5	25.9 (1)	23.32 (5)	>25.0
m_r............	>24.0	24.9 (2)	23.50 (8)	>25.0
m_i............	>23.0	···	···	···
$g - r$	···	1.0 (3)	−0.2 (1)	···
m_V^*	>23.5	25.4 (2)	23.38 (9)	>25.0
m_R^*	···	24.5 (3)	23.1 (1)	···
$B - V^*$.......	···	>−0.5	1.1 (1)	···
$(B - V)^*$.....	···	1.5 (3)	0.35 (9)	···
$m - M$	11.5 (5)	10.4 (5)	8.5 (5)	10.8 (5)
E_{B-V}	0.03	0.05	0.02	0.06
T (K).........	<9000	3700 ± 300	4300 ± 300	<8000
$\log(L/L_\odot)$	···	−3.55 ± 0.36	−4.0 ± 0.4	···

[a] Numbers in parentheses represent the uncertainty in the last digits quoted.

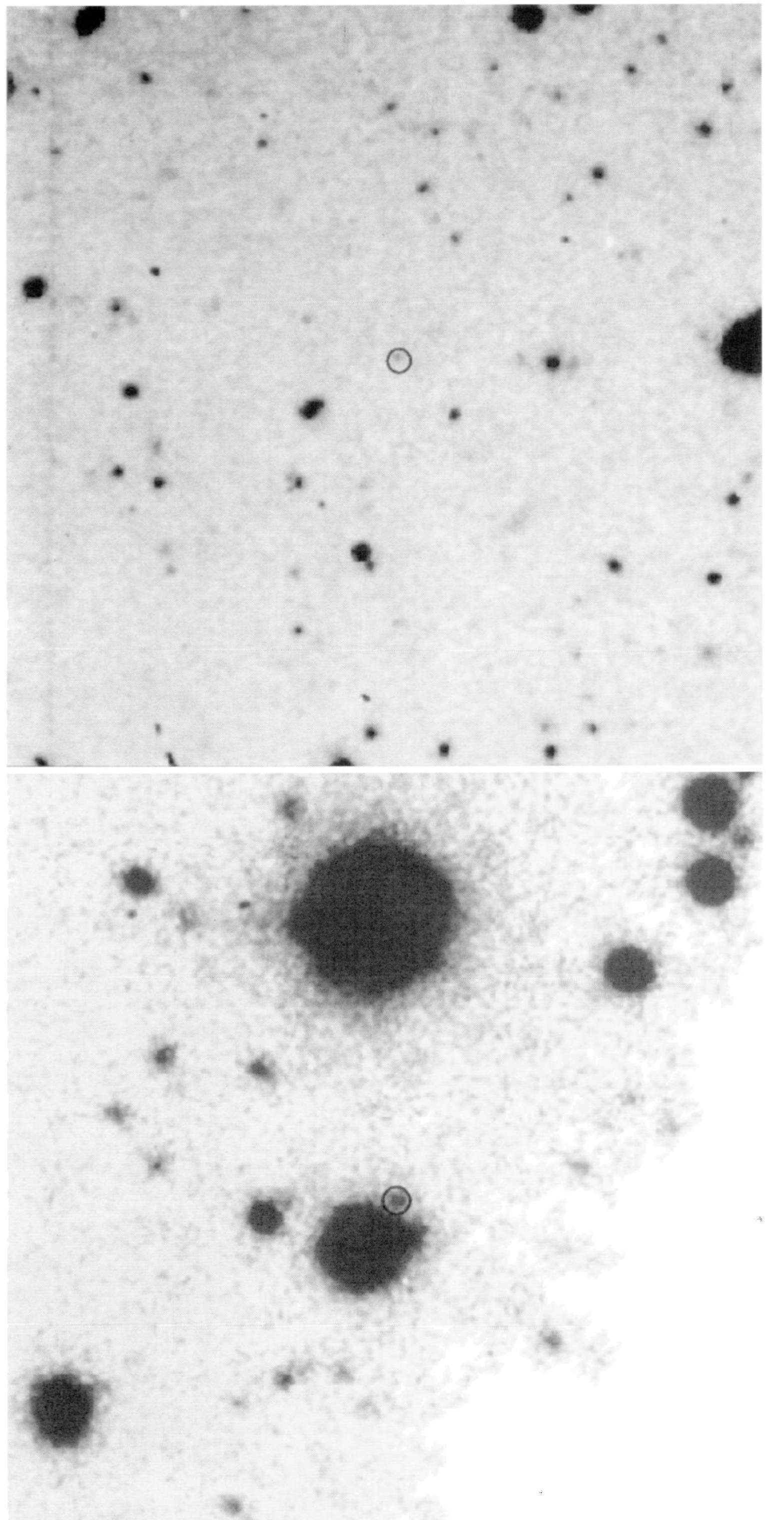

FIG. 1.—The top and bottom images correspond to PSR J1640+2224 and PSR J2145−0750, respectively. Each frame is 71''.0 × 71''.0. Both frames have been convolved with a 2 × 2 boxcar. The pixel scale is 0''.284 pixel^{-1}. The error circle of 1'' radius is centered on the radio pulsar timing position. North is up and east to the left. The top image is the sum of 3 g-filter exposures totaling 1800 s. The bottom image is a 600 s r-filter exposure. The brightest star visible is *HST* guide star 5788.0054, making astrometry particularly easy in this field. However, the bright star near the pulsar position makes photometry difficult.

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where $\dot{P}_{-20} = \dot{P}/10^{-20}$, P_{ms} is the pulsar spin period in milliseconds, I_{45} is the neutron star moment of inertia in units of 10^{45} g cm^2, r_9 is the WD radius in units of 10^9 cm, and a_{12} is the orbital separation in units of 10^{12} cm. For the energy output of PSR J0751+1807, the additional luminosity is $10^{-4.1}$ $L_\odot$ for a 0.15 $M_\odot$ WD with $r_9 = 1.7$ and $a_{12} = 0.14$. At a distance of 2 kpc the apparent magnitude would be $m_V = 26.8$. Our lower bound ($m_V > 23.5$) requires $T < 9000$ K and an age greater than $10^{8.9}$ yr. A main-sequence companion is ruled out by our data down to an M5 star ($M < 0.10$ $M_\odot$), since a main-sequence star more massive than M5 would have been detected at the distance to the pulsar. Furthermore, the minimum mass required by the mass function is about 0.1 $M_\odot$, so the companion to the pulsar in this system is clearly a WD, too old and distant to be detected in our images.

PSR J1640+2224.—The 3.2 ms pulsar J1640+2224 (Foster et al. 1995) has a companion in a 175 day orbit. The mass function allows $m_c > 0.24$ $M_\odot$ for a 1.4 $M_\odot$ neutron star, with a median $m_c = 0.3$ $M_\odot$. The characteristic spin-down time is greater than 20×10^9 yr. For a given pulsar age, we can determine the initial spin period (Camilo, Thorsett, & Kulkarni 1994), assuming magnetic dipole braking dominates the spin-down. Even if the pulsar is as old as the Galaxy, its spin-down rate ($\dot{P} < 2 \times 10^{-21}$) is so small that the current spin period is within 30% of the initial period. This spin period ($P_i \gtrsim 2$ ms) is nearly an order of magnitude larger than the equilibrium spin period of a 1.4 $M_\odot$ neutron star accreting at the Eddington rate with a 10^8 G magnetic field (Bhattacharya & van den Heuvel 1991). We note that the neutron star would have broken up before spinning up to $P \sim 0.2$ ms. The accretion rate must have been lower than the Eddington rate by a factor of about 40 in order to produce an initial spin period of 2 ms. If the pulsar is much younger, the initial spin period was correspondingly closer to the current period, and the accretion rate must have been even smaller.

In the standard evolutionary model, the pulsar was spun up by Roche lobe overflow during the giant phase of its companion. Hence, we expect that $m_c \simeq 0.31$ $M_\odot$, the mass of the helium core of a Roche lobe–filling giant in the currently observed orbit. The current observations reveal the cooled WD that collapsed from the helium core. There is a 5% probability of random coincidence of an object with $m_r < 25$ within 1″ of the pulsar position, based on the density of unresolved objects in this field. However, only about 10% of the unresolved objects in the field have colors and magnitudes similar to those expected for the pulsar's companion. A main-sequence star can be ruled out: a main-sequence star with $T = 3700$ K would have to be at 10–15 kpc (far out of the Galaxy at this latitude) to have the observed flux density ($m_g = 25.9$). The temperature and luminosity ($L = 10^{-3.55\pm0.36}$ $L_\odot$) are consistent with the helium WD cooling law calculated by Iben & Tutukov (1986) for $m_c = 0.3$ $M_\odot$ and age $t = (2 \pm 1) \times 10^9$ yr. Using the WD mass-radius relation (Savonije 1983), $r = 0.013(M/M_\odot)^{-1/3}R_\odot$, and the blackbody bolometric luminosity relation, the observed temperature and luminosity require a mass $m_c < 0.47$ $M_\odot$, consistent with the 0.31 $M_\odot$ predicted for the core mass of the Roche lobe–filling progenitor. The mass limit virtually guarantees that the companion is a helium WD and not a carbon-oxygen WD. General agreement of the observed colors and luminosity with the expectation based on evolutionary models makes the identification of the star as the pulsar companion secure. However, the luminosity ratio between a 0.15 $M_\odot$ WD and a 0.3 $M_\odot$ WD at the same temperature is only $10^{0.2}$. Improved photometry and measurement of the distance (perhaps from timing parallax) will be required to determine whether the WD J1640+2224 parameters deviate at a lower level from Roche lobe overflow and WD cooling model predictions.

PSR J2145−0750.—This 16 ms pulsar in a 6.8 day orbit has one of the longest spin periods and most massive non–neutron star companions of any MSP ($m_c > 0.43$ $M_\odot$). As mentioned earlier, the orbit is too small to have contained the progenitor of a WD companion. The progenitor star probably overflowed its Roche lobe on the asymptotic giant branch of stellar evolution and proceeded through a phase of common-envelope evolution (van den Heuvel 1994). The carbon-oxygen core mass for the donor star is expected to be close to 0.6 $M_\odot$.

We detect a source at the position of the pulsar (Fig. 1). However, the nearby bright star in the field makes accurate photometry difficult. Other observers have independently detected this source but find significantly different magnitudes (Bell et al. 1995). The B magnitude we estimate from $(B - V)^* + m_V$ is different from the B magnitude we actually measure. We attribute this to the difficulty of fitting the point-spread function and subtracting the nearby bright star, although it could be due to line emission or atmospheric opacity in the WD itself (Danziger et al. 1993; van Kerkwijk & Kulkarni 1995). The bluer $B - V$ corresponds to $T = 6800$ K. The model of Koester & Schonberner (1986) for $m_c = 0.6$ $M_\odot$ implies an age of 2×10^9 yr. The luminosity from such an object, $L = 10^{-3.5}$ $L_\odot$, requires a distance of 870 pc, nearly twice the estimate from the pulsar dispersion measure. The redder $B - V$ corresponds to a much cooler star, $T = 4300$ K, with a model age estimate of 6×10^9 yr. The 400 pc distance required to give the observed apparent magnitude agrees well with the 500 pc obtained from the dispersion measure. These values also agree with the $R - I$ colors calculated by Bell et al. (1995), although the magnitudes are not consistent. As for WD J1640+2224, a main-sequence star with these temperatures would have to be 10–15 times farther away, and therefore out of the Galaxy, to give the apparent magnitudes measured. The initial spin period for PSR J2145−0750 was probably within 50% of the current period, for the limits on age determined from cooling and with the assumption of magnetic dipole braking. The standard spin-up model (Bhattacharya & van den Heuvel 1991) indicates that, for the inferred initial period, the final accretion rate was a factor of 60 below the Eddington rate. Significant improvement in the photometry will be possible with *HST* imaging, which eliminates the influence of the bright nearby star on the results. Improvements on the distance estimate will give constraints on the WD mass and age.

PSR J2229+2643.—This 3 ms pulsar is too old and distant for the companion to be detected in our images. At 25×10^9 yr, the characteristic spin-down age does not constrain the true age of the system, which we expect to be less than the age of the Galaxy. If the pulsar is at the dispersion-derived distance of 1.4 kpc and its age is close to 8×10^9 yr, similar to the age of the Galactic disk, we would expect $m_V > 26.8$, much fainter than our limit of about 25. Our limiting magnitude requires a WD older than about 10^9 yr.

4. DISCUSSION

The two new sources detected, WD companions of PSR J1640+2224 and PSR J2145−0750, can be added to a small but growing list of optical identifications of MSP companions. The large actual ages of our systems (as estimated through cooling times) argue against the postaccretion decay of magnetic fields on timescales shorter than about 10^9 yr, consistent with previous results (Kulkarni 1986; Bell et al. 1993). The parameters derived for the sources in our study are consistent with the predictions based on Roche lobe overflow of the progenitor giant star followed by WD cooling, but the parameters are still poorly constrained and the cooling models still have large uncertainties. Stringent tests of the models demand more sensitive studies of the new sources and independent distance estimates to improve color and luminosity measurements. Eventual detection of a very low mass companion like the one predicted for PSR J0751+1807 will be particularly useful in probing the limits of validity of current theories for Roche lobe overflow and WD cooling.

With additions to the list of known sources, population studies will be possible, making a better connection between the low-mass X-ray binary (LMXB) phase and the recycled pulsar phase of evolution. The cooling ages we find in our limited sample, all exceeding 10^9 yr, reverse the trend in earlier detections. A recently discovered WD companion (PSR J1012+5307) is only 3×10^8 yr old, more than an order of magnitude less than its spin-down age (Lorimer et al. 1995; Bailyn 1995). The surprising youth of this source led to speculation that many MSP systems are much younger than originally thought, thus increasing the MSP birthrate. This would exacerbate any LMXB/MSP birthrate discrepancy (Kulkarni & Narayan 1988). The advanced age of our sample suggests that the relative youth of one of the earliest detections results from a selection effect: the brightest (and hence first discovered) companions necessarily will be the closest (PSR J0437−4715) and the hottest/youngest (PSR J1012+5307). A larger sample of sources with measured WD cooling ages, as well as improvements in the cooling models, particularly for low-mass WDs, will be necessary before using WD cooling ages to determine how much higher the MSP birthrate is than the birthrate derived using spin-down ages.

The characteristic spin-down times significantly exceed the cooling times estimated for PSR J1640+2224 and PSR J2145−0750, as expected for these and many other MSPs, since their spin-down times exceed the age of the Galactic disk. Although this eliminates the spin-down time as an independent age estimate for use in testing cooling models, cooling times allow us to estimate the initial spin period, which is determined by the accretion rate at the end of the LMXB phase. The estimates we have made of the initial spin period assume magnetic dipole braking, a reasonable assumption for slow pulsars, but untested for millisecond pulsars. If higher order multipoles dominate, the initial periods will be shorter than those we have estimated. For both pulsars, the accretion rate is found to be nearly 2 orders of magnitude below the Eddington rate. In the case of PSR J1640+2224, this is within a factor of 2 or 3 of the expected rate for the final stages of mass transfer driven by nuclear evolution of the helium star (Bhattacharya & van den Heuvel 1991). An alternative explanation for not reaching the equilibrium period for Eddington accretion at the current magnetic field strength is that the spin-up occurred when the magnetic field was a factor of 10 higher. If the final factor of 10 drop in the field occurs fast enough, too little mass is accreted for the pulsar to reach the equilibrium period of the lower field strength. An understanding of the relationship between the decrease in magnetic field strength and the amount of matter accreted will be necessary before we can determine whether the extrapolated initial periods reflect the equilibrium spin period for the currently observed magnetic field. For the progenitor of PSR J2145−0750, the final stage was probably a short-lived period of common-envelope evolution in which the amount of mass accreted was insufficient to cause significant spin-up before the envelope was ejected. The spin period thus reflects an earlier accretion rate, perhaps from the giant star wind (van den Heuvel 1994).

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