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THE NEUTRON STAR–HELIUM WHITE DWARF POPULATION IN THE GALACTIC DISK

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ABSTRACT

The population of low-mass binary pulsars in the Galactic disk has grown considerably in the past few years. By "low mass," we mean that the companion to the neutron star is, or is very likely to be, a helium white dwarf. The distribution of these objects in the P-$\dot{P}$ plane, where P is the rotation period, suggests both that their initial periods after spin-up are near 3 ms and that the age of the population is near 5 Gyr. This initial spin-up is similar to the inferred rotation rates in low-mass X-ray binaries (LMXBs) with dual-line quasi-periodic oscillations at kilohertz frequencies. Furthermore, the age of 5 Gyr is consistent with models of the LMXB population as evolving from stars with masses just above 1 $M_\odot$, although significant uncertainties remain in observationally derived birthrates of the radio and X-ray binaries. The observed distribution of minimum masses in the low-mass binary pulsar population requires a distribution of actual masses and is not the result of a random distribution of inclination angles. This distribution further leads to the conclusion that these millisecond pulsar systems do not have random inclination angles. A preference for orthogonal magnetic and spin axes is a possible configuration.

Subject headings: pulsars: general — stars: neutron — stars: statistics — white dwarfs — X-rays: stars

1. INTRODUCTION

There are 20 millisecond rotation period pulsars with companions that are almost certainly helium white dwarfs. While the pulsar primary in these systems is most likely the remnant of a main-sequence star whose mass is above 8 $M_\odot$, the white dwarf secondary stars are the end products of main-sequence stars with masses closer to 1 $M_\odot$ (Webbink, Rappaport, & Savonije 1983). As the secondary stars leave the main sequence, they fill their Roche lobes and transfer matter and angular momentum onto the neutron stars. The neutron star is spun up to millisecond periods over 10–100 Myr and probably has its magnetic field reduced in the process (Chen & Ruderman 1993; van den Heuvel & Bitzaraki 1995). During the mass transfer phase the systems are observable as low-mass X-ray binaries. Bhattacharya & van den Heuvel (1991) and Verbunt (1993) have written recent reviews of these topics.

Our understanding of the link between the low-mass pulsar binaries and low-mass X-ray binaries has been questioned by a number of authors because of discordant estimates of their population statistics. Kulkarni & Narayan (1988) first raised the question about the consistency of birthrates of the two classes. Their analysis suffered from extremely low statistics of the binary pulsars. Coté & Pylyser (1989) reduced the inconsistency by consideration of the effects of magnetic braking and gravitational radiation, and Tavani (1991) discussed the effects of evaporation of the secondary star by pulsar spin-down luminosity. In the intervening years, the millisecond binary pulsar population in the Galactic disk has grown considerably. Phinney & Kulkarni (1994) review the relative birthrates issue and come to the conclusion that the low-mass, short orbital period pulsar binaries must pass through a brief X-ray phase of some 10 million years and are not simply progenitors of the slowly evolving, low-mass X-ray population seen today. Lorimer (1995) revisited the birthrate topic after further discoveries were reported and concludes that the birthrate inconsistency between low-mass binary pulsars (LMBPs) and low-mass X-ray binaries (LMXBs) is further reduced, but possibly not eliminated if selection effects in the binary pulsar population, such as minimum luminosity, are considered. For example, the Lorimer sample considers objects down to a 400 MHz luminosity of 2.5 mJy kpc^2, while Tauris et al. (1994) have found a pulsar with a luminosity of 0.06 mJy kpc^2. Lorimer further mentions that an equal consideration of selection effects in the X-ray binary population could be important. We proceed with the view that the two populations are intimately linked, but keep an open mind about the fundamental uncertainty that may be present.

The current large number of millisecond pulsars in this common evolutionary class of low-mass binaries allows a study of their population parameters: initial spin period following the LMXB phase that spins up the neutron star, perpendicular dipole magnetic field strength at the surface, birthrate, and lifetime. The recent detection by the *Rossi X-Ray Timing Explorer* of pairs of kilohertz quasi-periodic oscillations in LMXBs that drift in frequency as the luminosity changes along with the tentative assignment of the stable frequency difference with the neutron star spin frequency (see summary by van der Klis 1997) provides a further boundary condition to the population study.

In this paper, we first discuss the selection of low-mass binary, millisecond period pulsars from the known binary pulsars. This discussion includes a review of important limits in the detection of millisecond pulsars. The period derivatives, which are essential for a discussion of pulsar ages, are corrected for the apparent acceleration that results from their transverse motion (Shklovskii 1969; Camilo, Thorsett, & Kulkarni 1994). The population is then compared to that resulting from a range of choices of parameters. The conclusion from this study is that the initial period after spin-up is around 3 ms and that the birthrate has been steady for about 5 Gyr. These parameters are compared to those of LMXB population models. In addition, we compare the parameters of the neutron star–helium white dwarf (NS-WD[He]) population to the other LMBP systems: those with carbon-oxygen white dwarf secondary stars and those with planetary and substellar mass companions. An analysis of the distribution of minimum companion masses in the low-mass binary pulsars leads to two conclusions: (1) there is a skewed distribution of true companion masses and (2) orbital inclinations are not random.

2. THE LOW-MASS BINARY, MILLISECOND SPIN PERIOD PULSAR POPULATION

The orbital parameters of a binary pulsar provide a good estimate of the minimum companion mass, if one assumes the mass of the pulsar. The companion mass may be larger than this estimate owing to the unknown inclination of the orbit. If we assume a mass of 1.4 $M_\odot$ for the pulsar, then a secondary star with a minimum mass above 0.5 $M_\odot$ is either a CO white dwarf or a second neutron star. A CO white dwarf secondary requires evolution of a 2–8 $M_\odot$ companion through to the asymptotic branch, which, in turn, requires an initially wide binary orbit (Bhattacharya & van den Heuvel 1991). The most commonly observed minimum mass in millisecond pulsar binaries is near 0.1–0.2 $M_\odot$. These pulsars come from systems with initial orbital periods of a day or more and main-sequence masses near 1.2 $M_\odot$ (Webbink et al. 1983). The mass of the degenerate companions must be at least around 0.12 $M_\odot$, which is the Schönberg-Chandrasekhar limit, unless evaporation is important (Tavani 1991). These low companion mass binaries are the principal focus of this paper. The large ratio of systems with secondary stars that apparently evolved from low-mass main-sequence companions in comparison to those that evolved from higher mass companions makes qualitative sense if the companion stars follow the standard initial mass function (IMF). However, a quantitative comparison of the relative populations requires exploration of a range of hypotheses for companion mass distribution and orbital distribution before and after the neutron star formation event (see, e.g., Dewey & Cordes 1987). The magnitude of the linear momentum impulse at the birth of a neutron star is an additional issue, as discussed by Dewey & Cordes (1987) and more recently by van den Heuvel & van Paradijs (1997).

Table 1 lists the selected millisecond rotation period, low companion mass binary pulsars along with their rotation periods (P), corrected period derivatives ($\dot{P}$), orbital periods (P_b), estimated distances (D), and minimum companion masses based on 1.4 $M_\odot$ neutron star primaries (m_2). The neutron star masses are likely to be 0.5 ± 0.5 $M_\odot$ larger than 1.4 $M_\odot$ due to mass transfer from the secondary. Thus, the minimum companion masses are further underestimated by a factor of approximately $20 \pm 20\%$. The most recent publication containing these parameters is given in the last column. The period derivatives listed in Table 1 are corrected for a kinematic bias, $PD\mu^2/c$, where μ is the proper motion (Shklovskii 1969; Camilo, Thorsett, & Kulkarni 1994). Measured proper motions are used where available, but in general a transverse velocity of 75 km s^{-1} is assumed. This velocity is consistent with Lorimer's (1995) study of the z-distribution of these pulsars that requires a one-dimensional rms velocity of 50 km s^{-1}. Ramachandran & Bhattacharya (1997) also suggest small space velocities for millisecond pulsars in their comparative study of pulsar and LMXB velocities.

Figure 1 displays the P-$\dot{P}$ distribution of the millisecond-period pulsars with companion objects. The squares show the locations of the binary millisecond-period pulsars with He white dwarf secondary companions discussed above (LMBPs or NS-WD[He]s). Included in Figure 1, but not in Table 1, are three intermediate-mass binary pulsars (IMBPs) with CO white dwarf companions (NS-WD[CO]s) (*circles*) and three pulsars with planetary and substellar mass companions (*triangles*). Most of the pulsars included in Figure 1 are from large-area surveys. One exception is J0218+4232 (Navarro et al. 1995) and, as such, should be

TABLE 1

PULSAR PARAMETERS

Pulsar	P (ms)	$\dot{P}$ (10^{-20} s s^{-1})	P_b (days)	D (kpc)	$m_{2,\min}$	Reference
0034−0534......	1.877	0.60	1.6	1.0	.14	1
0218+4232......	2.323	7.42	2.0	10.0	.16	2
0437−4715......	5.757	1.90	5.7	0.14	.14	3
0613−0200......	3.062	1.00	1.2	2.2	.13	4
0751+1807......	3.479	0.57	0.3	2.0	.13	5
1012+5307......	5.256	1.20	0.6	0.5	.11	6
1045−4509......	7.474	1.90	4.1	3.2	.16	7
1455−3330......	7.987	0.60	76.2	0.7	.27	4
1603−7202......	14.842	0.90	6.3	1.6	.29	8
1640+2224......	3.163	0.03	175.0	1.2	.24	9
1643−1224......	4.622	3.20	147.0	5.0	.13	4
1713+0747......	4.570	0.80	67.8	1.0	.27	10
1804−2718......	9.343	3.80	11.1	1.2	.21	8
B1855+09	5.362	1.42	12.3	1.0	.24	11
1911−1114......	3.626	1.20	2.7	1.6	.12	8
B1953+29	6.133	2.95	117.0	5.4	.18	12
2019+2425......	3.935	0.80	77.0	0.9	.32	13
2129−5721......	3.726	2.00	6.6	2.6	.14	1
2229+2643......	2.978	0.02	93.0	1.4	.12	13
2317+1439......	3.445	0.24	2.5	1.9	.17	13

REFERENCES.—(7) Bailes et al. 1994; (3) Bell et al. 1995a; (1) Bell et al. 1995b; (10) Camilo, Foster, & Wolszczan 1994; (13) Camilo et al. 1996; (11) Kaspi, Taylor, & Ryba 1994; (4) Lorimer et al. 1995a; (6) Lorimer et al. 1995b; (8) Lorimer et al. 1996; (5) Lundgren, Zepka, & Cordes 1995; (9) Lundgren et al. 1996; (2) Navarro et al. 1995; (12) Rawley et al. 1988

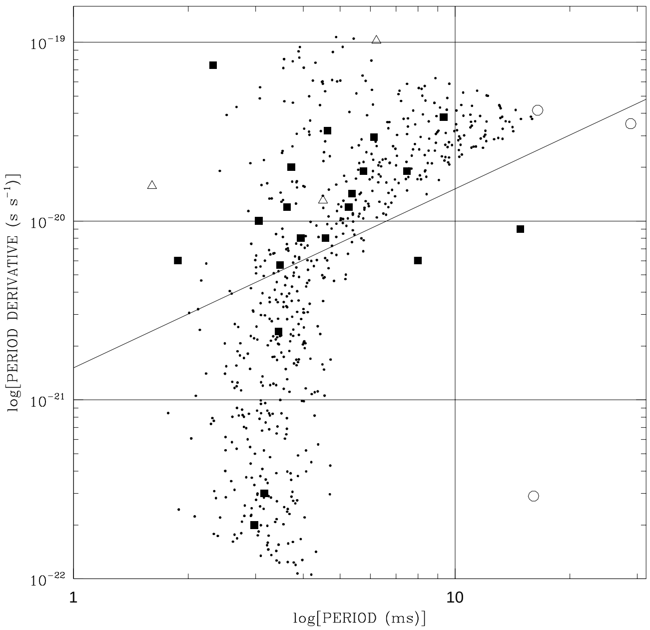

FIG. 1.—Open squares show the locations of binary millisecond-period pulsars with He white dwarf secondary companions. The observed period derivatives have been corrected for kinematic bias. The triangles show the locations of three pulsars with planetary and substellar mass companions. The dots are the result of a model of the pulsar He white dwarf binaries with the following parameters: maximum age of 5×10^9 yr; surface magnetic field between 3×10^6 and 5×10^9 G; initial period of 3 ms with Gaussian distribution whose rms is 0.6 ms. Selection against short-period pulsars in the search has been applied to an initial population of 1000 pulsars.

given less weight in a population study. Dispersive smearing and sampling limitations make surveys increasingly incomplete below a period of about 3 ms. For example, Foster et al. (1995) and Manchester et al. (1996) state minimum flux densities for detection that grow by factors of 1.0, 1.4, 2.3, and 5.4 as the rotation period decreases from 12 to 7, 3, and 1.5 ms, respectively. The number of visible pulsars scales in inverse proportion to these minimum flux densities for a spherical distribution of pulsars. Therefore, the paucity of pulsars below 3 ms is due, in part, to selection effects (Lorimer et al. 1996). Kramer et al. (1997) do not find a strong luminosity relationship with spin parameters within the millisecond pulsar population. This reduces our concern with flux-limited sample selection effects that are important in population analyses of slow pulsars. Similarly, the pulse profiles of these pulsars are particularly broad and do not clearly depend on pulse period. Therefore, period-dependent beaming effects, which would affect the probability of detection and also play an important role in slow pulsar population studies, do not affect this study.

An isochrone is shown in Figure 1 for 10 Gyr, based on the assumption that the current period is much larger than the initial period following spin-up of the neutron star during its LMXB phase, $P/2\dot{P}$. However, if the current period is comparable to the initial period (P_0), then the spin-down age for magnetic dipole radiation, which produces a braking index of 3, is $P/2\dot{P}[1-(P_0/P)^2]$. In this case, isochrones bend asymptotically to P_0 as periods shorten. In Figure 1, the NS-WD(He) binaries with spin periods at and above 5 ms are concentrated significantly *above* the 10 Gyr isochrone, while those near 3 ms are *at and even below* the isochrone. As mentioned by other authors (Camilo, Nice, & Taylor 1996; Lundgren et al. 1996), the three pulsars below the line—J1640+2242, J2229+2643, and J2317+1439—must have had initial periods close to their present periods to keep their spin-down ages under that of the Galaxy.

An explanation for the distribution of most of the NS-WD(He) binaries in Figure 1 is that the minimum periods of these stars are near 3 ms *and* that their maximum ages are near 5 Gyr *and* that their magnetic fields, as estimated from the spin parameters, extend over a wide range. This possibility was explored by developing a Monte Carlo population with a range of three parameters: (1) mean initial period, (2) standard deviation of initial period with Gaussian probability density function, and (3) a maximum age. Figure 2*a* displays the birthrates of low-mass binary pulsars with the assumptions of (1) the main-sequence secondary stars of the neutron star–main-sequence star progenitors of low-mass binary pulsars following a standard IMF with differential slope of $M^{-2.35}$; (2) a main-sequence lifetime of 6 Gyr $(M_2/1.2\ M_\odot)^{-3.5}$; and (3) a steady state production in the Galaxy that began 12 Gyr ago. Thus, the helium white dwarf companions (m_2) in low-mass binary pulsars are formed from main sequence stars with mass M_2, starting 12–6$(M_2/1.2\ M_\odot)^{-3.5}$ Gyr ago. The neutron star in this binary came from a high-mass main-sequence star promptly after the formation of the Galaxy. The ordinate of the age distributions in Figure 2*a* are proportional to the frequency of occurrence of M_2 in the IMF. Figure 2*b* displays on a logarithmic scale the relative numbers of systems with a range of main-sequence secondary star masses from 1.1 M to 1.4 $M_\odot$. In our Monte Carlo model we use a relative number function appropriate for a single mass of approximately 1.2 $M_\odot$. The probability density in age for the model observable population is then just in proportion to

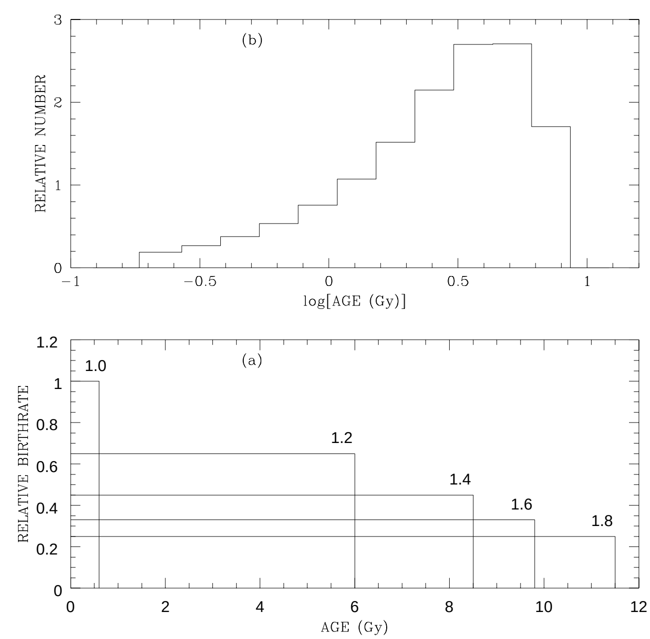

FIG. 2.—(*a*) Relative birthrates of low-mass binary pulsars under the assumptions that the companion stars have masses ranging from 1.0 to 1.8 $M_\odot$. There has been steady state star production since the birth of the Galactic disk 12 Gyr ago, and the companion stars follow a standard IMF in relative numbers. (*b*) Relative numbers of systems produced for masses between 1.1 and 1.4 $M_\odot$ on a logarithmic age scale.

the age. One thousand stars are selected randomly. These are binned by period and randomly culled as a function of period to model the search completeness factors discussed above. Only crude adjustment of parameters to match the observed distribution is done owing to the limited data available. Further support for and constraints on the parameters are provided below. The model distribution in Figure 1 has the following parameters: maximum age of 5 Gyr, surface magnetic field between 3×10^6 and 5×10^9 G with a uniform distribution in the log, and initial period of 3 ms with a Gaussian distribution whose rms is 0.6 ms. The minimum period distribution is not well constrained on the lower side due to selection effects.

The age of 5 Gyr is significantly less than that of the oldest globular clusters and the oldest disk stars. While this age could be the result of the lifetime of the pulsar emission process, the more probable explanation is that the origin of these spun-up neutron stars follows a full lifetime of the secondary stars. Vassiliadis & Wood (1995) give main-sequence ages of 11.3 and 2.7 Gyr for masses (M) of 1.0 and 1.5 $M_\odot$, respectively; i.e., age depends on $M^{-3.5}$. Webbink et al. (1983) argue that the LMXB population requires companion masses around 1.2 $M_\odot$. This is set on the high side by the stringent requirement for stable mass transfer and on the low side for significant production during the lifetime of the Galaxy. Recent estimates for the oldest stars in the Galaxy, from dating of metal-poor globular clusters, is 12.2 ± 1.8 Gyr (Salaris, Degl'Innocenti, & Weiss 1997). The difference between the age of the Galaxy and the lifetime of the low-mass binary progenitor stars is then about 6 Gyr, which influenced the choice of the Monte Carlo model age parameter.

If the objects presented in Table 1 are a homogeneous subset, then the minimum mass estimates may be the result of the combined effects of the distributions of the inclinations, the neutron star masses, and the companion masses. While there will be a correlation between the companion mass and the neutron star mass due to conservative mass transfer, we cannot determine the effect of the correlation with any certainty. Indeed, if there is conservative mass transfer, then given the small range in $m_{2,\mathrm{min}}$, the neutron stars will have masses around 2.4 ± 0.2 $M_\odot$ and the effect is small. Figure 3*a* displays a frequency-of-occurrence histogram of the calculated minimum masses using 1.4 $M_\odot$ for the neutron star mass. The effect of random inclinations (i) over a hemisphere would lead to a distribution of minimum masses ($m_{2,\mathrm{min}}$) for fixed neutron star (m_1) mass and fixed companion mass (m_2) that depends on $z/(1 - z^2)^{1/2}$, where $z \equiv m_{2,\mathrm{min}}/m_2 = \sin i$.[1] This distribution, which is plotted in Figure 3*b*, has the opposite skew to that in Figure 3*a*. Clearly the observed distribution is a measure of the distributions mainly in m_1 and m_2. The sharp peak at 0.125 $M_\odot$ has no tail extending to lower masses. This tail must be present if the inclinations are random (Fig. 3*b*). We must then conclude that the inclinations are *not* random. As the pulsars in these systems are spun up by accretion of orbital angular momentum, their spin axes are expected to be aligned with the orbital angular momentum. One way of producing a favored inclination is to have radiation prefer-

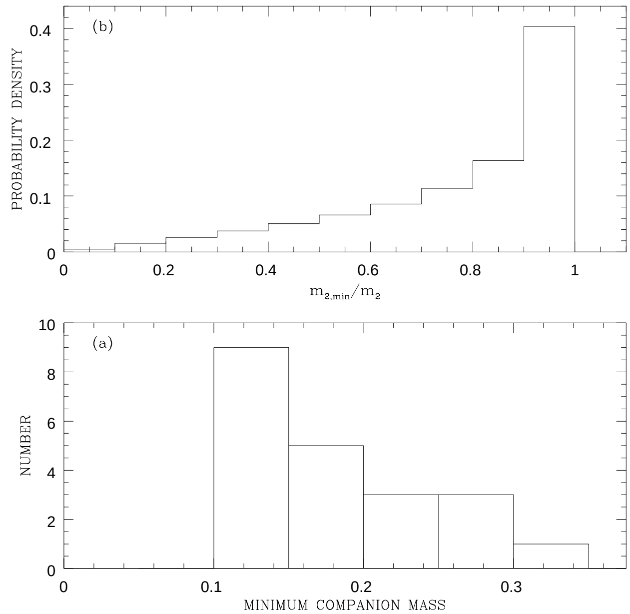

FIG. 3.—(*a*) Histogram of the numbers of binary pulsars is shown as a function of the minimum companion mass ($m_{2,\mathrm{min}}$), assuming that the neutron star has a mass of 1.4 $M_\odot$. (*b*) Expected distribution of minimum companion masses for a fixed true companion mass (m_2) and a random inclination angle.

entially beamed in the equatorial plane of the spinning and orbiting neutron star. The magnetic field evolution scenario of Chen & Ruderman (1993) favors just such a preference due to their conclusion that millisecond pulsars in the Galactic disk have offset, orthogonal dipole magnetic fields. However, their model predicts a high incidence of interpulses that is not seen in these pulsars. The compilation by Kramer et al. (1997) shows that these pulsars typically have 2–4 adjacent components with typical separations of 20°. Significant beaming of the low-mass binary pulsars will exacerbate the LMBP-LMXB birthrate problem mentioned in § 1.

The three objects with very small companion masses in Figure 1 are *not* low-inclination versions of the low-mass binary pulsars: B1257+12 is included since it has a planetary system (Wolszczan 1994); B1957+20 and J2051−0827 are high-inclination systems with bloated 0.03 $M_\odot$ companions that produce eclipses (Fruchter, Bookbinder, & Bailyn 1995 and Stappers et al. 1996, respectively). While J2051–0827 has a characteristic age comparable to that of the low-mass binary population, 5 Gyr, B1257+12 and B1957+20 are unusually young. The seven single millisecond pulsars in the Galactic disk have typical ages of 5 Gyr. PSR B1937+21, the original millisecond pulsar (Backer et al. 1982), is notable for its youth. The similarity of ages between the single pulsars and low-mass binary pulsars supports the view that they also evolve from binary systems where the companion mass is of order 1.2 $M_\odot$. The remnant of the companion must be removed by either evaporation or coalescence in a common envelope stage.

3. DISCUSSION

While this study began prior to the discovery of quasi-periodic oscillations (QPOs) at kilohertz frequencies in LMXB fluctuation spectra, there is now a corroborative clue in the results discussed above that strengthens the link

[1] The probability density function for random inclinations is $\sin i$ over the interval $[0, \pi/2]$. The probability $P(i < i_0)$ is then $1 - \cos(i_0) = 1 - (1 - \sin^2 i_0)^{1/2} = 1 - (1 - z_0^2)^{1/2}$. The desired probability density for z is then $z/(1 - z^2)^{1/2}$.

between LMXBs as progenitors of the NS-WD(He) systems. Van der Klis (1997) summarizes the rapidly evolving situation. There are eight LMXBs with dual peak QPO activity. In all cases, the *difference* between the QPO peak frequencies is 250–350 Hz, roughly 4–3 ms. In four cases, modulation is also detected at this difference frequency, or its second harmonic. As the LMXB luminosity varies, the QPO frequencies vary, but in all cases except one, the difference frequency remains constant. While no model is accepted for the origin of these modulations, there is widespread belief that the stable frequency is that of the spin rate (or half the spin rate) of the underlying neutron star. The link between the LMXBs and the low-mass binary pulsars is uniformly accepted, although there is continuing debate on population statistics (e.g., Kulkarni & Narayan 1988; Verbunt 1993; Phinney & Kulkarni 1994; Lorimer 1995). The rough agreement between what is probably the *current* periods of the LMXB neutron stars and the inferred initial periods of the NS-WD(He) binaries lends support both to the interpretation of the LMXB difference frequency as neutron star spin and to the population model with its initial period distribution that is presented here. The known orbital periods of LMXBs are somewhat smaller than those of the low-mass binary pulsars. If there is significant orbital period evolution in the final stages of the LMXB population, there is then likely to be spin-rate evolution as well. In this case we would expect the inferred initial periods of the low-mass binary pulsars to be smaller than those inferred from the kHz QPO frequencies of the LMXBs. This is certainly consistent with what is known, given the strong selection effects against the discovery of 1–3 millisecond period pulsars.

The location of the three certain NS-WD(CO) systems in Figure 1 indicates that the initial period distribution for these pulsars is centered, or is extended to, significantly larger periods than that for the more well-sampled NS-WD(He) systems. If the larger initial periods of these pulsars are confirmed by the increasing statistics of new pulsar discoveries, then we will be forced to conclude that the angular momentum accretion onto the companion neutron stars in these intermediate-mass binary systems is less than that for the low-mass systems discussed above. The shorter evolution time of the companion star is one possible reason for this. The different evolutionary history of these intermediate mass binary pulsars, including clues based on their eccentricities, is discussed further by Camilo et al. (1996).

There are two certain neutron star–neutron star binaries in the Galactic disk. The spin-down ages of B1913+167 and B1534+12 are 6.3×10^7 and 2.5×10^8 yr, while the gravitational decay times of their orbits owing to gravitational radiation are 3×10^8 and 1.2×10^{10} yr, respectively. B1913+167 thus has a rotation age consistent with its orbit age. On the other hand, based on the millisecond pulsar ages of at least 5 Gyr discussed here, there could be many systems like B1534+12 in the Galaxy.

Two of the very low-mass companion object systems have unusually young ages relative to 5 Gyr: B1957+20 and B1257+12. Based on Figure 2*a*, we suggest that these arise from neutron star–main-sequence binaries with 1 $M_\odot$ or less secondary stars. In this case, the spun-up pulsars must be less than 1 Gyr old.

4. CONCLUSIONS

The age of the population of low-mass binary, millisecond-period pulsars is established by the evolution time of the typical secondary star in the progenitor system since the formation of the Galactic disk, about 5 Gyr. This age is consistent with models of the low-mass X-ray binaries that are the immediate progenitor systems, although significant uncertainties concerning the relative birthrates of the radio and X-ray binary populations remain. The surface dipole magnetic field of the neutron stars is between 3×10^6 and 5×10^9 G, using the conventional conversion from spin parameters. There is no sign of luminosity, magnetic field, or dipole geometry evolution over 5 Gyr. The long lifetime of millisecond pulsars, in general, can then be used to assess the birthrate and evolutionary history of other subclasses of millisecond pulsars.

The initial period distribution of the low-mass binary, millisecond-period pulsars extends to about 3 ms. The lower edge of this distribution is uncertain because of the selection effects in current searches. Searches now in progress will be able to clarify this distribution. The distribution is consistent with the interpretation of the difference frequency of kilohertz QPO features in LMXB fluctuation spectra as the underlying neutron star spin frequency. The uncertainty of a factor of 2 in relating the neutron star spin frequency to the observed QPO frequencies prevents developing any firm conclusion about the period evolution between the LMXB and LMBP phases of these systems.

The minimum companion mass distribution of the low-mass, binary, millisecond-period pulsars is not consistent with a random distribution of inclinations. The probable cause for a lack of randomness is a preference for beaming in the equatorial plane of the neutron star rotation that, owing to spin-up via accretion, is parallel to the orbital plane. Measurement of inclinations by pulsar timing via the Shapiro delay will allow confirmation of this conjecture.

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REFERENCES

Backer, D. C., et al. 1982, Nature, 300, 615
Bailes, M. F., et al. 1994, ApJ, 425, L41
Bell, J. F., et al. 1995a, ApJ, 440, L81
———. 1995b, ApJ, 452, L121
Bhattacharya, D., & van den Heuvel, E. P. J. 1991, Phys. Rep., 203, 1
Camilo, F., Foster, R. S., & Wolszczan, A. 1994, ApJ, 437, L39
Camilo, F., Nice, D. J., & Taylor, J. H. 1996, ApJ, 461, 812
Camilo, F., Thorsett, S. E., & Kulkarni, S. R. 1994, ApJ, 421, L15
Chen, K., & Ruderman, M. 1993, ApJ, 408, 179
Coté, J., & Pylyser, E. H. P. 1989, A&A, 218, 131
Dewey, R. J., & Cordes, J. M. 1987, ApJ, 321, 780
Foster, R. S., et al. 1995, ApJ, 454, 826.
Fruchter, A. S., Bookbinder, J., & Bailyn, C. D. 1995, ApJ, 443, L21
Kaspi, V. M., Taylor, J. H., & Ryba, M. F. 1994, ApJ, 428, 713
Kramer, M., et al. 1997, A&A, in press
Kulkarni, S. R., & Narayan, R. 1988, ApJ, 335, 755
Lorimer, D. R. 1995, MNRAS, 274, 300
Lorimer, D. R., et al. 1995a, ApJ, 439, 933
———. 1995b, Nature, 376, 393
———. 1996, MNRAS, 283, 1383
Lundgren, S. C., Cordes, J. M., Foster, R. S., Wolszczan, A., & Camilo, F. 1996, ApJ, 458, L33
Lundgren, S. C., Zepka, A. F., & Cordes, J. M. 1995, ApJ, 453, 419
Manchester, R. N., et al. 1996, MNRAS, 279, 1235

Navarro, J., de Bruyn, A. G., Frail, D. A., Kulkarni, S. R., & Lyne, A. G. 1995, ApJ, 455, L55
Phinney, E. S., & Kulkarni, S. R. 1994, ARA&A, 32, 591
Ramachandran, R., & Bhattacharya, D. 1997, MNRAS, 288, 565
Rawley, L. A., Taylor, J. H., & Davis, M. M. 1988, ApJ, 326, 947
Salaris, M., Degl'Innocenti, S., & Weiss, A. 1997, ApJ, 479, 665
Shklovskii, I. S. 1969, Soviet Astron., 13, 562
Stappers, B. W., Bessell, M. S., & Bailes, M. 1996, ApJ, 473, L119
Tauris, T., et al. 1994, ApJ, 428, L53
Tavani, M. 1991, ApJ, 366, L27
van der Klis, M. 1997, preprint (astro-ph/9704272)
van den Heuvel, E. P. J., & Bitzaraki, O. 1995, A&A, 297, L41
van den Heuvel, E. P. J., & van Paradijs, J. 1997, ApJ, 483, 399
Vassiliadis, E., & Wood, P. R. 1993, ApJ, 413, 641
Verbunt, F. 1993, ARA&A, 31, 93
Webbink, R. F., Rappaport, S., & Savonije, G. 1983, ApJ, 270, 678
Wolszczan, A. 1994, Science, 264, 538