

Optical Studies of Companions to Millisecond Pulsars

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Abstract. Optical observations of the companions of pulsars can help determine the properties of the binaries, as well as those of their components, and give clues to the preceding evolution. In this review, we first describe the different classes of binary pulsars, and we present a table with a summary of what is known about their optical counterparts. Next, we focus on the class of pulsars that have low-mass, helium-core white dwarf companions. We discuss attempts to determine the masses of both components using optical spectroscopy, and compare the pulsar spin-down ages with cooling ages of the white dwarfs. We confirm that, for a given age, the lowest-mass white dwarfs are much hotter than the more massive ones, consistent with recent evolutionary models, although with one glaring exception. We discuss the case of PSR B0820+02, where the cooling age indicates a braking index less than 3, and we conclude by describing how cooling ages can be used to test formation scenarios for PSR J1911–5958A, a pulsar binary in the outskirts of NGC 6752.

1. Binary Pulsars and Their Evolutionary Histories

In Table 1, we list all pulsars in binaries outside of globular clusters. One sees that their properties vary widely, but one can identify different types on the basis of the spin and orbital properties. For instance, systems separate in clusters by inferred companion mass and orbital period, as can be seen in Figure 1. Below, we briefly describe the different groups and their evolutionary histories (for reviews, see Phinney & Kulkarni 1994; Stairs 2004).

PSR+OB(e) Pulsars with massive stellar companions, which formed in binaries where one star went supernova. The pulsars are like young, isolated pulsars. Probably, there are many more PSR+OB(e) systems in which the pulsar is hidden by the companion's stellar wind. There should also be pulsars with lower-mass companions,

but as yet no secure identifications have been made (a candidate is PSR B1820–11; Phinney & Verbunt 1991).

PSR+NS Pulsars formed second in massive binaries, with the first-formed neutron star as a companion. For the one system known, the first-born neutron star is a pulsar as well, but recycled (see below).

PSR+CO/ONeMg-WD In binaries with two stars just below the critical mass required to form a neutron star, the originally more massive star will evolve first and leave a white dwarf. In the process, it may transfer sufficient amounts of matter to make the originally lighter star massive enough to explode, leaving a newly formed pulsar in an eccentric orbit around a massive white dwarf.

Rec.-PSR+NS In binaries with a massive star and a neutron-star companion, the star will eventually evolve. Unless the orbit is very wide, it will overflow its Roche lobe, and unstable mass transfer to the neutron star will ensue, leading to a spiral in. The accretion of matter on the neutron star spins it up and, by mechanisms unknown, reduces the magnetic field. The resulting ‘recycled’ pulsar is left in a binary with another neutron star when the remaining helium core is heavy enough to go supernova. The orbit will be eccentric. These systems are also called ‘high-mass binary pulsars’ (HMBP). For one system, the companion neutron star is a pulsar as well.

Rec.-PSR+CO-WD If, in the above scenario, the helium core is not massive enough to explode, it will form a white dwarf with a CO or ONeMg core and a helium envelope. A massive white dwarf can also be left if the companion of the pulsar evolved up to the AGB before overflowing its Roche lobe. The latter scenario may lead to more accretion, and thus a neutron star spun up to faster periods and with a more strongly reduced magnetic field. The white dwarf might still have a hydrogen envelope. In either case, the orbit will be circular. These systems are also referred to as ‘intermediate mass binary pulsars’ (IMBP).

Rec.-PSR+He-WD If the companion of a neutron star is a low-mass star, the mass transfer that ensues when it evolves and overfills its Roche lobe is stable. A lot of mass is transferred, leading to fast spin periods and low magnetic fields, as well as, presumably, greatly increased mass. If mass transfer started before the helium flash, a helium-core white dwarf will be left, with a hydrogen envelope. If it started afterwards, a white dwarf with a CO core will be formed, and the atmosphere may be either hydrogen or helium. In either case, one expects a circular orbit. These systems are also called ‘low-mass binary pulsars’ (LMBP).

Rec.-PSR+WD Recycled pulsars are also found with companion masses more similar to brown dwarfs. These companions likely started with higher masses, but lost most of their mass in a long X-ray binary phase. The systems are also called ‘very low-mass binary pulsars’ (VLMBP) or, because of the strong irradiation and evaporation observed, ‘black widow pulsars.’

The various evolutionary scenarios lead to predictions for the properties of the binary pulsars we observe. In particular for the recycled pulsars with low-mass white-dwarf companions, which evolved via stable mass transfer, the predictions seem secure: there should be a relation between companion mass and orbital period, one between eccentricity and orbital period, and the neutron-star masses should have increased (for a review, see Phinney & Kulkarni 1994).

Of these predictions, the second has been verified (Phinney & Kulkarni 1994), but the lack of accurate masses prevented stringent tests of the other two. With continuing high-precision timing, however, the situation has changed. For instance, Nice et al. (in

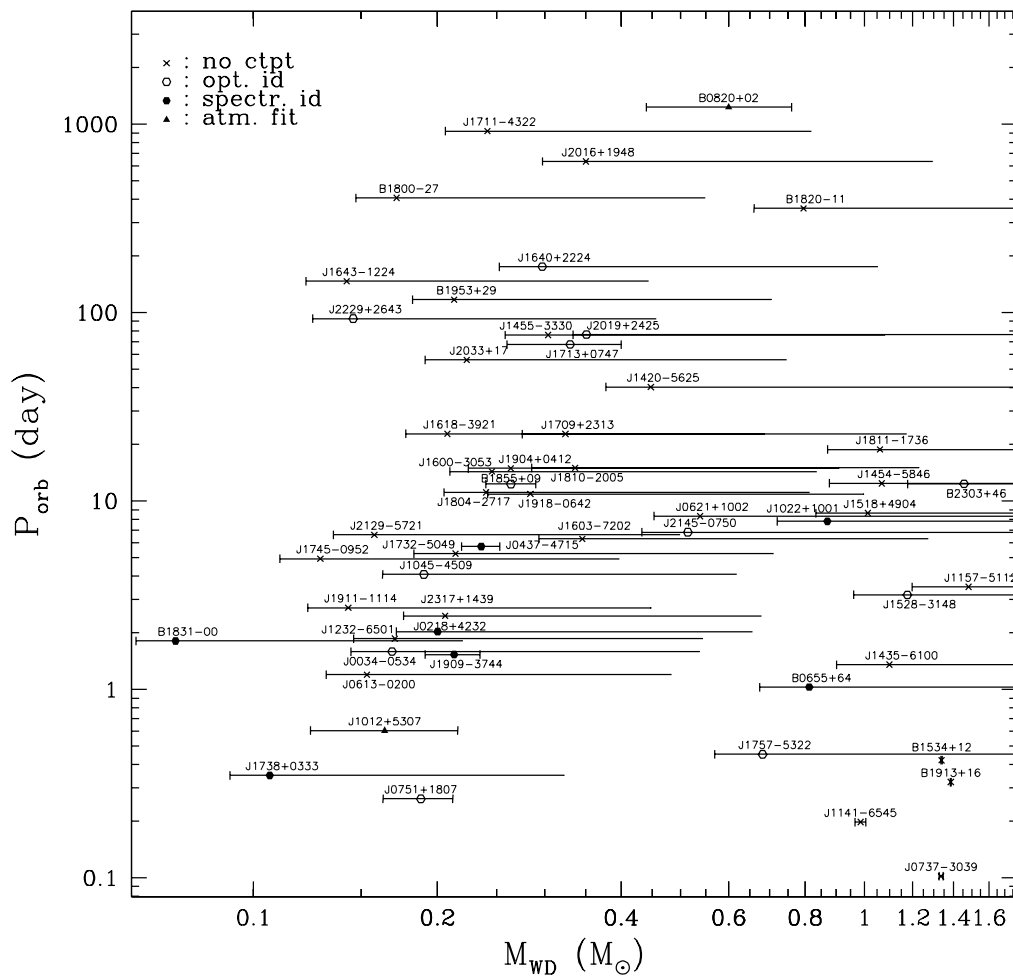


Figure 1. Orbital period as a function of companion mass for all binary pulsars outside globular clusters with degenerate companions. Measured masses have 95% confidence error bars. For other systems, the masses are statistical, assuming a $1.4 M_{\odot}$ pulsar mass and a 60° inclination. The horizontal bar indicates a range in inclination from 90° (left handle) to 18° (right side). For each system, the marker indicates what is known about the optical counterpart (see legend and Table 1).

this volume) have uncovered clear evidence that the neutron stars are more massive than the typical $1.35 M_{\odot}$ inferred from double-neutron-star binaries (Thorsett & Chakrabarty 1999; these should have accreted little).

Timing measurements, as well as optical studies (see below), have also yielded a number of accurate companion masses, which allow a much improved test of the relation between companion mass and orbital period. In Figure 2, we show these masses, with model predictions of Tauris & Savonije (1999) overdrawn. The agreement is impressive, especially when one considers that the models were produced before the accurate masses became available.

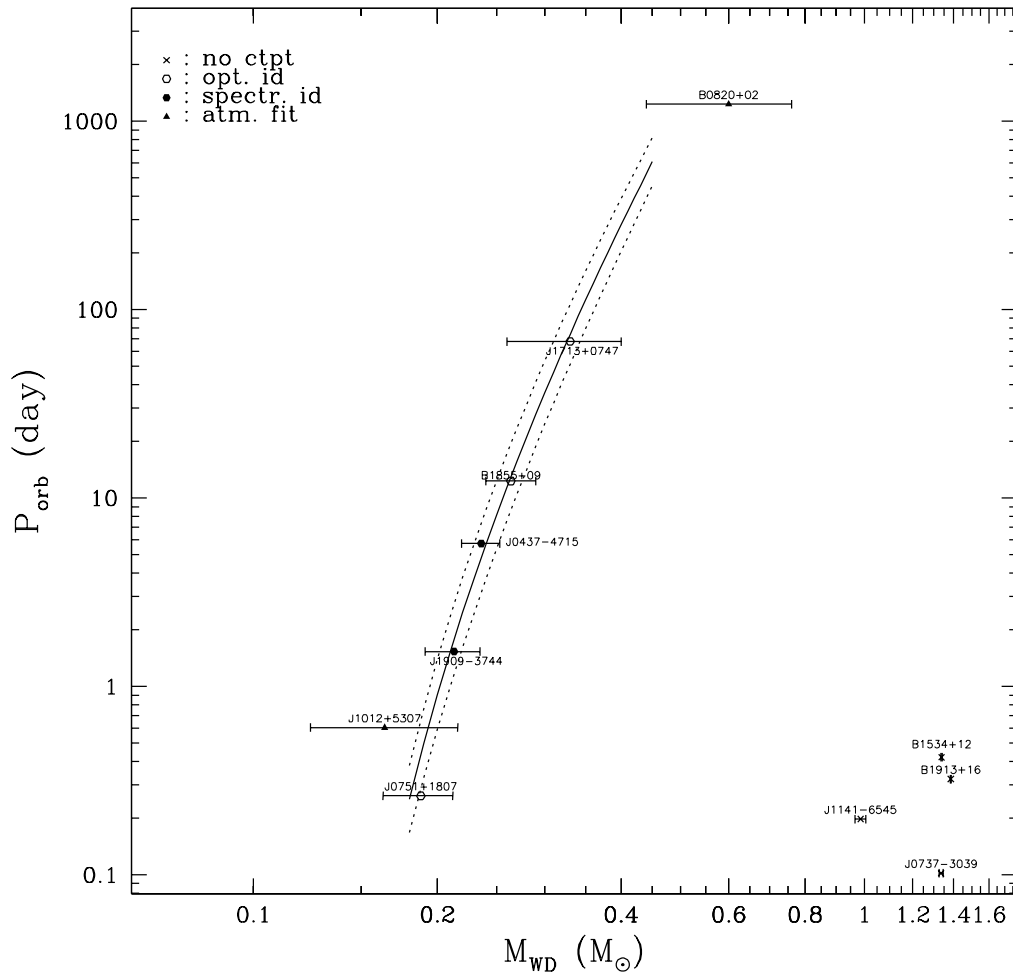


Figure 2. Orbital period as a function of companion mass for all binary pulsars with measured masses (shown with 95% confidence error bars). Overdrawn are predictions from the evolutionary calculations of Tauris & Savonije (1999). The different lines are for different progenitor metallicities; there is some additional uncertainty related to the mixing-length parameter.

2. Optical Counterparts

In Table 1 we also summarise what is known optically. One sees that for the pulsars with massive stellar companions, which should be bright, two out of three are identified; the third (PSR J1740–3052) is highly obscured. Also for the two ‘back widow’ pulsars, the two strongly irradiated, bloated, brown-dwarf-mass companions have been identified.

For the pulsars likely to have white-dwarf companions, 22 out of 49 have been identified optically (see also Fig. 1). Of these, 7 have spectral types and a further 9 have some colour information. As expected from evolutionary considerations, the spectral type of the one more massive companion indicates a helium atmosphere, while a hydrogen atmosphere is found for companions inferred to be low-mass white dwarfs (e.g., Van Kerkwijk & Kulkarni 1995).

Table 1. Optical properties of binary pulsars in the field.

Name	P (ms)	DM (pc/cc)	$\log \tau_c$ (yr)	P_{orb} (d)	Optical information [References]
<i>PSR+OB(e)</i>					
J0045–7319	926.3	105	6.52	51.17	B1V, $V = 16.19$ [kjb+94,bbs+95]
B1259–63	47.8	147	5.52	1236.72	B2e, $V = 10.05$ [jml+92,simbad]
J1740–3052	570.3	741	5.55	231.03	[st++01]
<i>PSR+NS</i>					
J0737–3039B	2773.5	49	7.70	0.10	
<i>PSR+CO/ONeMg-WD</i>					
J1141–6545	393.9	116	6.16	0.20	$R > 23.4$
B2303+46	1066.4	62	7.47	12.34	$B = 26.6$, $B - R = 0$ [vkk99]
<i>Rec.-PSR+NS (HMBP)</i>					
J0737–3039A	22.7	49	8.32	0.10	
J1518+4904	40.9	12	10.37	8.63	$B > 24.5$, $R > 23$ [nst96]
B1534+12	3.8	12	7.39	0.42	
J1811–1736	104.2	477	8.96	18.78	
B1820–11 ^a	279.8	429	6.51	357.76	
B1913+16	59.0	169	8.03	0.32	
<i>Rec.-PSR+CO/ONeMg-WD (IMBP)</i>					
J0621+1002	28.9	37	9.98	8.32	$R > 24$
B0655+64	195.7	9	9.66	1.03	DQ7, $V = 22.2$ [kul86,vkk95]
J1022+1001	16.5	10	9.78	7.81	$V = 23.1$, $V - I = 0.4$ [lfc96]
J1157–5112	43.6	40	9.68	3.51	$R > 23.7$:
J1435–6100	9.3	114	9.78	1.35	$R > 23.1$
J1454–5846	45.2	116	8.94	12.42	$R > 24.9$
J1528–3146	60.8	19	...	3.18	$R = 23.9$:
J1757–5322	8.9	31	9.73	0.45	$R = 24.6$:
J2145–0750	16.1	9	9.93	6.84	$V = 23.7$, $V - I = 0.7$ [lfc96]

Note: Optical information without reference refers to unpublished results of ourselves. Colons indicate insecure photometry. For an overview of white-dwarf spectral types, see Wesemael et al. (1993). Briefly, ‘D’ is for degenerate dwarf, ‘Q’ indicates the presence of carbon features in the spectrum, ‘A’ the presence of hydrogen, ‘C’ the absence of any spectral features. The subtype n is a measure of temperature, $T_{\text{eff}} \simeq 50400/n$.

^a B1820–11 may have a low-mass star as companion rather than a neutron star (Phinney & Verbunt 1991).

For most of the 27 unidentified pulsar, white dwarf binaries, there are upper limits of roughly 24th magnitude. These are predominantly the result of a systematic campaign to find all objects bright enough to do spectroscopy, which, as will become clear below, allows one to obtain the most interesting results.

Table 1 (Cont'd). Optical properties of binary pulsars in the field.

Name	P (ms)	DM (pc/cc)	$\log \tau_c$ (yr)	P_{orb} (d)	Optical information	[References]
<i>Rec.-PSR+He-WD (LMBP)</i>						
J0034-0534	1.9	14	9.78	1.59	$I=24.8, V-I > 2.0$	[lfc96]
J0218+4232	2.3	61	8.68	2.03	DA6, $V=24.2$	[bvkk03]
J0437-4715	5.8	3	9.20	5.74	DC12, $V=20.8$	[dbdv93]
J0613-0200	3.1	39	9.71	1.20	brightish star nearby ^b	
J0751+1807	3.5	30	9.85	0.26	$R=25.1, R-I=0.9$	[bvkk04]
B0820+02 ^a	864.9	24	8.12	1232.40	DA3, $V=22.8$	[kr00]
J1012+5307	5.3	9	9.69	0.60	DA6, $V=19.6$	[llfn95,vkbbk96]
J1045-4509	7.5	58	9.83	4.08	$R \sim 24$:	
J1232-6501	88.3	239	9.24	1.86	$R > 24$	
J1420-5625	34.1	65	9.90	40.29	crowded field	
J1455-3330	8.0	14	9.72	76.17	$R > 24$	
J1600-3053	3.6	52	9.78	14.35	$R > 24$	
J1603-7202 ^a	14.8	38	10.18	6.31	$R > 24$ (v.faint ctpt?)	
J1618-3921	12.0	118	9.55	22.80	$R > 24$	
J1640+2224	3.2	18	10.25	175.46	$V=26.0, V-I=1.4$	[lfc96]
J1643-1224	4.6	62	9.60	147.02	$R \sim 23$::	
J1709+2313	4.6	25	10.31	22.71	$R > 24$	
J1711-4322	102.6	192	6.89	920.2	pos. too unc.	
J1713+0747	4.6	16	9.93	67.83	$V=26.0, V-I=1.9$	[lfc96]
J1732-5049	5.3	57	9.79	5.26	$R > 24$	
J1738+0333	5.8	34	9.61	0.35	DA6, $V \sim 21$	
J1745-0952	19.4	64	9.51	4.94	$R > 24$	
B1800-27	334.4	166	8.49	406.78	crowded field	
J1804-2717	9.3	25	9.56	11.13	$R > 24$	
J1810-2005	32.8	240	9.54	15.01	$R > 24$	
B1831-00 ^a	521.0	89	8.89	1.81	$R=22.0, R-K=2.3$	
B1855+09	5.4	13	9.68	12.33	$V=25.9, V-I=1.7$	[vkbbk00]
J1904+0412	71.1	186	10.01	14.93	$R > 24$	
J1909-3744	2.9	10	9.52	1.53	DA6, $V \sim 21$	[jbvk+03]
J1911-1114	3.6	31	9.61	2.72	$R > 24$ (v. faint ctpt?)	
J1918-0642	7.6	27	9.70	10.91	$R > 24$	
B1953+29	6.1	105	9.51	117.35	brightish star nearby ^b	
J2016+1948	64.9	34	...	635.04		
J2019+2425	3.9	17	9.95	76.51	$I=25.0, V-I > 1.1$	[lfc96]
J2033+17	5.9	25	9.93	56.31	pos. too unc.	
J2129-5721	3.7	32	9.45	6.63	$R > 24$	
J2229+2643	3.0	23	10.51	93.02	$R \sim 25$:	
J2317+1439	3.4	22	10.35	2.46	$R > 24$	
<i>Rec.-PSR+BD (VLMBP)</i>						
B1957+20	1.6	29	9.18	0.38	$R=19.4 \dots > 24$	[cvpr95, fbb95]
J2051-0827	4.5	21	9.75	0.10	$R=22.5 \dots 25.5$	[svkbbk01]

^a B0820+02 has a CO-WD companion. J1603-7202 may be an IMBP, given its high mass function. B1831-00 is hardly recycled; it may have formed differently.

^b These stars are likely unassociated, but prevent deep searches.

3. Radial Velocities and Masses

For the counterparts bright enough for spectroscopy, one can model the spectrum, and determine a precise temperature and surface gravity for the white dwarf. Combined with white-dwarf mass-radius relations from cooling models, these yield the white-dwarf mass, which can be used to verify the predictions from binary evolution. If the orbit is short enough, one can also measure radial velocities and determine the radial-velocity amplitude. Combined with the precise radial-velocity amplitude of the pulsar (derived from timing), this yields the mass ratio and thus, with the mass of the white dwarf, the neutron-star mass.

For the first relatively bright counterpart discovered, that of PSR J0437–4715, the result was disappointing: the spectrum was featureless (Danziger et al. 1993). The temperature of ~ 4000 K is too low for any features to appear.

For the even brighter counterpart of PSR J1012+5307, however, strong hydrogen lines were present in the spectrum, and a model-atmosphere and radial-velocity analysis were done by two groups (Van Kerkwijk, Bergeron, & Kulkarni 1996; Callanan, Garnavich, & Koester 1998). Unfortunately, the results were less constraining than hoped. First, the radial-velocity amplitudes found by the two teams were different. It turned out this was related to a reduction error by Van Kerkwijk et al. (1996); a re-reduction of the original data, complemented with more recent results, yields a radial-velocity amplitude of $199 \pm 10 \text{ km s}^{-1}$, consistent with the $218 \pm 10 \text{ km s}^{-1}$ found by Callanan et al. (1998). This result should still improve, once small remaining systematic effects have been taken into account. From the two estimates, the current best estimate of the mass ratio is $M_{\text{NS}}/M_{\text{WD}} = 10.0 \pm 0.7$.

A second discrepancy between the two studies was the value of the surface gravity inferred: Van Kerkwijk et al. (1996) found $\log g = 6.75 \pm 0.07$, while Callanan et al. (1998) inferred $\log g = 6.34 \pm 0.20$. For this difference, the underlying cause turned out to be two different sets of model atmospheres used (by P. Bergeron and D. Koester, respectively). When the spectra of Van Kerkwijk et al. were fitted using the Koester models, a surface gravity consistent with that of Callanan et al. is found (D. Koester, pers. comm.).

Finally, it was found that for the very low masses involved, the mass-radius relation was less securely known than expected. Coincidentally, the slightly different approaches taken by the two teams compensated the differences in surface gravity, leading to the same final white dwarf mass, $0.16 \pm 0.02 M_{\odot}$.

The above mass and mass ratio correspond to a neutron star mass of $1.6 \pm 0.2 M_{\odot}$, where the uncertainty is dominated by the uncertainty in the white-dwarf mass. If instead we use the white-dwarf mass expected from the models of Tauris & Savonije (1998), $M_{\text{WD}} = 0.193 \pm 0.007$ (see Fig. 2), we infer a neutron star mass of $1.9 \pm 0.2 M_{\odot}$. This is a large mass, but similar to is found for PSR J0751+1807 by Nice et al. (in this volume). Clearly, it will be worthwhile to try to determine the white-dwarf mass more accurately.

This procedure was also tried on another short-period pulsar binary, PSR J0218+4232. This system is substantially fainter ($V = 24.2$; Table 1), and, unfortunately, it turned out to be beyond the capabilities of the then-available instrumentation: while an accurate temperature could be determined, no useful constraints could be derived on the surface gravity and radial-velocity amplitude (Bassa, Van Kerkwijk, & Kulkarni 2003a). Obviously, the current large uncertainties are somewhat discouraging. Fortunately, on all fronts improvements are being made. First, two more bright counterparts to recycled pulsars have been discovered, to PSR J1909–3744 and J1738+0333 (see Table 1). Both have spectra similar to J1012+5307, and thus similar temperatures and surface gravities. Of the two, PSR J1909–3744 is particularly interesting, as the orbit is sufficiently edge-on to allow for an accurate determination of the white-dwarf mass from Shapiro delay (Jacoby et al. 2003). Combined with much improved white-dwarf mass-radius relations

(from detailed cooling models; see below), this implies we will know the surface gravity of the white dwarf, which we can use to calibrate the model-atmosphere analysis.

The second improvement is that more blue-sensitive and more stable spectrographs are now available on large telescopes, and hence more precise radial-velocity curves can be measured. It should be possible to obtain mass ratios to better than $\sim 5\%$ accuracy. Observing campaigns of both new pulsar binaries are underway.

We conclude by mentioning one last system, PSR B0820+02, for which it has been possible to derive an accurate companion mass, $M = 0.60 \pm 0.08$ (Koester & Reimers 2000). This mass is similar to the masses found for isolated white dwarfs, for which the white-dwarf model atmospheres and mass-radius relations are well understood. Hence, it should be reliable. Unfortunately, the system is unsuitable for determining the neutron star mass, as the orbit is too wide to determine an accurate radial-velocity curve. However, as we will see below, the accurate white-dwarf mass and temperature allow for interesting constraints on the cooling age.

4. Cooling versus Spin-down Age

After the last bit of mass is transferred from the progenitor of the white dwarf to the neutron star, two independent clocks start running. The first clock is the millisecond pulsar, which will turn on and start slowing down. Assuming a spin-down torque $\propto \nu^n$, the pulsar age is given by

$$t_{\text{psr}} = \frac{P}{(n-1)\dot{P}} \left[1 - \left(\frac{P_0}{P} \right)^{n-1} \right], \quad (1)$$

where $P \equiv 1/\nu$ is the current spin period, \dot{P} is its rate of change, P_0 is the period when the pulsar began spinning down following cessation of mass transfer, and $n = \nu\ddot{\nu}/\dot{\nu}^2$ is the “braking index,” equal to 3 under the assumption of magnetic dipole radiation. For $n = 3$ and $P_0 \ll P$, $t_{\text{psr}} \simeq \tau_c \equiv P/2\dot{P}$, where τ_c is the pulsar “characteristic age.”

The second clock is the white dwarf. After the remaining envelope has been burned off, the white dwarf can only radiate its internal heat, making it cool down as time goes by. In principle, it is fairly easy to estimate the cooling, as the thermal structure of the white dwarf is simple. The heat is stored in the non-degenerate ions in the white dwarf interior, which is kept nearly isothermal due to the efficient heat conduction by degenerate electrons. The cooling rate is determined by the much less efficient radiative heat transport near the white dwarf’s atmosphere.

In practice, there are complications. Apart from difficulties in modelling the radiative opacities and dealing with convection, there are two additional physical processes that play a role. First, at low temperatures, the ion gas in the core starts to crystallise. The latent heat released temporarily keeps the white dwarf warmer, but once gone, allows for much more rapid cooling. This effect is particularly important for more massive, carbon-oxygen white dwarfs. Second, for white dwarfs with relatively thick residual hydrogen envelopes, the pressure at the bottom can be sufficiently high for significant pycno-nuclear fusion, keeping the white dwarf warm longer. We will return to this below.

The possible use of comparing pulsar and white-dwarf ages was realized immediately upon the first detection of optical emission from white-dwarf counterparts (Kulkarni 1986). For the white dwarf accompanying PSR B0655+64, a relatively low temperature, ~ 7000 K, was inferred, which implied an age of ~ 2 Gyr. This meant that pulsar magnetic fields could not decay completely on this timescale, as had been common wisdom at the time.

The first systematic comparison between spin-down and cooling ages was done by Hansen & Phinney (1998a,b). Since they had to rely on estimated masses, their re-

sults were uncertain, but two clear discrepancies stood out: for PSR J1012+5307, the inferred cooling age was far shorter than the characteristic age, while for PSR B0820+02, the cooling age was significantly longer. We discuss both discrepancies in turn.

4.1. PSR J1012+5307 and Other Short-Period Binaries

Already in their discovery paper of PSR J1012+5307's optical counterpart, Lorimer et al. (1995) noted that the white dwarf was much hotter than expected given the pulsar's characteristic age. They suggested that the problem might lie in the pulsar age: if the initial period to which the pulsar was spun up was similar to the current one (i.e., $P_0 \simeq P$ instead of $P_0 \ll P$ in Eq. 1), then the pulsar age could be equal to a short cooling age. Alberts et al. (1996), however, suggested the white-dwarf age had been underestimated: given the low mass, the hydrogen layer on the white dwarf could be quite thick, and residual hydrogen burning could keep the white dwarf hot. Indeed, this effect had already been found by Webbink (1975), in a general study of the evolution of helium white dwarfs in close binaries.

A flurry of modelling followed, confirming the likely presence of a thick hydrogen layer (Driebe et al. 1998, 1999), and adding complications, such as the duration of the semi-detached phase in which the companion is becoming a white dwarf (Sarna, Antipova, & Muslimov 1998). At first, the new models seemed to suggest that most low-mass white-dwarf companions should be fairly bright, but this was disproven by the discovery of a very faint counterpart to PSR B1855+09 (Van Kerkwijk et al. 2000). This led to more careful considerations of the effects of shell flashes during the formation (e.g., Schönberner, Driebe, & Blöcker 2000), and to the effects of element diffusion on these flashes (Sarna, Ergma, & Gerškevič-Antipova 2000; Althaus, Serenelli, & Benvenuto 2001a,b).

The current consensus appears to be that below a certain critical mass, the hydrogen layer should be thick and white dwarfs should be relatively hot, $\sim 10^4$ K even when several Gyr old. Above the critical mass, shell flashes occur, and the hydrogen layer will be too thin to sustain significant residual fusion; after several Gyr, those more massive white dwarfs will have cooled to below 5000 K. The precise value of the critical mass is not known, but, since the shell flashes result from CNO burning, almost certainly depends on metallicity (Sarna et al. 2000; Serenelli et al. 2002).

Until recently, there was not much supporting observational evidence. Indeed, except for PSR J1012+5307, all identified white dwarf counterparts were rather cool, implying thin hydrogen envelopes. Could it be that thick envelopes did not occur at all, and that PSR J1012+5307 was re-born with $P_0 \simeq P$ after all (Bassa et al. 2003a)?

Additional evidence for the presence of thick hydrogen envelopes was uncovered with the identification of rather bright and hot white-dwarf counterparts to two new pulsars with large characteristic ages (PSR J1909–3744 and PSR J1738+0333; see Table 1). With those, it has become possible to try to determine empirically the critical mass below which hydrogen layers will be thick. Unfortunately, we do not have accurate masses for most white-dwarf companions. However, we can use the orbital period as a proxy, as this should correlate fairly tightly with the companion mass (see Fig. 2 and Sec. 1).

In Table 2, we list the properties for those low-mass binary pulsars that either have periods less than 3 days or have measured companion masses. The final column lists whether a thick or a thin hydrogen envelope is required to understand the observed temperature (assuming the white-dwarf cooling age is similar to the characteristic age). One sees that for all systems with orbital periods in excess of 1.55 d, thin hydrogen envelopes are inferred, while below that period they are likely thick (with one exception; see below). For the system just below the critical period, PSR J1909–3744, we have a mass estimate from Shapiro delay. The preliminary results from Jacoby et al. (2004, in preparation), is $0.203 \pm 0.006 M_\odot$. This is slightly more massive than found from

Table 2. Hydrogen layer properties for helium WD companions.

Name	d_{TC}^{a} (kpc)	d_{CL}^{a} (kpc)	$\log \tau_{\text{c}}$ (yr)	P_{orb} (d)	M_{WD}^{b} (M_{\odot})	$T_{\text{eff}}^{\text{c}}$ (kK)	H layer
J0751+1807	2.0	1.1	9.85	0.26	0.16–0.21	3	thin
J1738+0333	1.9	1.4	9.61	0.35		9	thick
J1012+5307	0.5	0.4	9.69	0.60	0.12–0.20	8.5	thick
J0613–0200	2.2	1.7	9.71	1.20			
J1909–3744	1.1(+0.3/–0.2)		9.52	1.53	0.19–0.22	8	thick
J0034–0534	1.0	0.5	9.78	1.59		< 4	thin
J1232–6501	10	6.2	9.24	1.86			
J0218+4232	5.9	2.6	8.68	2.03		8	thin
J2317+1439	1.9	0.8	10.35	2.46		< 4:	thin
J1911–1114	1.6	1.2	9.61	2.72		< 5:	thin
J0437–4715	0.139 ± 0.003		9.20	5.74	0.20–0.27	4	thin
B1855+09	0.9(+0.4/–0.2)		9.68	12.33	0.24–0.40	5	thin
J1713+0747	1.1(+0.5/–0.3)		9.93	67.83		3.5	thin
B0820+02 ^d	1.86 ± 0.13		8.12	1232.40	0.44–0.76	15	thin

^a Distances are inferred from the dispersion measure using the Taylor & Cordes (1993) and the Cordes & Lazio (2002) models of the Galactic electron distribution. Distances with uncertainties (1σ) are from parallax measurements (J1909: Jacobi et al., in prep.; J0437: [vsbb+01]; B1855: [ktr94]; J1713: [cfw94]) and from modelling the white-dwarf spectrum (B0820: [kr00]).

^b Masses are from Shapiro delay (J0751, B1855, J1713: [nss04]; J1909: Jacobi et al., in prep.; J0437: [vsbb+01]), and from modelling the white-dwarf spectrum (J1012: [vkbk96,cgk98]; B0820: [kr00]).

^c Temperatures are from colours or spectra, except for J2317+1439 and J1911–1114, for which the limits were derived from the magnitude limit, combined with the Cordes & Lazio distance. These are marked with a colon to indicate they are uncertain.

^d B0820+02 has a CO WD companion, but formed like a LMBP.

the models of, e.g., Althaus et al. (2001b), which suggest that $0.196 M_{\odot}$ white dwarfs should still have thin envelopes. However, given the uncertainties (e.g., in metallicity; Serenelli et al. 2002), the agreement seems satisfactory.

While the results above paint a consistent picture, there is one exception: for PSR J0751–1807, a low temperature is measured (Bassa, Van Kerkwijk, & Kulkarni 2004). A low temperature had already been indicated by earlier limits of Lundgren et al. (1996a), and Ergma, Sarna, & Gerškevitš-Antipova (2001) suggested the hydrogen envelope might have been reduced shortly after the mass transfer ceased, due to irradiation by the pulsar (which would be particularly effective in such a close binary). Intriguingly, however, our photometry seems to indicate that the white dwarf has no hydrogen whatsoever, but instead a helium atmosphere.

4.2. PSR B0820+02 and its Surprisingly Cool White Dwarf

The second discrepancy identified by Hansen & Phinney (1998b) was that the cooling age for PSR B0820+02 was significantly longer than the characteristic age. This was confirmed by Koester & Reimers (2000), who analysed spectra of the optical companion

and inferred $T_{\text{eff}} = 15000 \pm 800$ K and $\log g = 7.98 \pm 0.13$. Combined with cooling models, this yields a mass of $0.60 \pm 0.08 M_{\odot}$. This mass implies a CO core, and is typical for an isolated white dwarf, not unexpected given the very wide orbit, and the fact that the pulsar appears to have been recycled only very mildly ($P = 0.9$ s; $B \simeq 3 \times 10^{11}$ G).

For a mass of $0.6 M_{\odot}$, the implied cooling age is 221 ± 11 Myr, which is significantly above the pulsar's characteristic age, $\tau_c = 130$ Myr. Koester & Reimers (2000) argue that the white-dwarf cooling models for these masses are secure, and hence that the pulsar age must be larger than the characteristic age. From Eq. 1, one sees that the only way to do that is to decrease the braking index n ; consistency with the cooling age would then require $n = 2.2$.

If true, the above implies that pulsar spin-down is different from magnetic dipole braking not just for young pulsars (e.g., Lyne 1996), but also for older ones. As yet, however, the conclusion is less firm than it might appear: the uncertainty in the age listed by Koester & Reimers (2000) does not seem to include the uncertainty in the mass of the object. For a less massive white dwarf, the cooling age would be reduced (e.g., 150 Myr for a $0.5 M_{\odot}$ white dwarf; see also Schönberner et al. 2000). This can be verified with better spectra.

4.3. Application to PSR J1911–5958A in NGC 6752

With the cooling models in quantitative agreement with the observations, it has become possible to use them. One particularly interesting case is PSR J1911–5958A in the globular cluster NGC 6752. This binary is puzzling as it is very far, ~ 3.3 half-mass radii outside the core (D'Amico et al. 2002; also Possenti et al., in this volume), and it is unclear how it could have gotten there. Colpi et al. (2002) investigated different possibilities, and found it was difficult to produce the system either from a primordial binary or by a scattering or exchange event. Instead, they suggested that the binary may have been scattered by a binary composed of two fairly massive black holes. In this scenario, the binary would already have formed before the scattering event.

An age estimate could be used to distinguish between the various possibilities. For a primordial origin or an older binary being scattered by a binary black hole, the white dwarf would most likely be rather old. If the white dwarf was formed during or shortly after an exchange, however, it could not be much older than the ~ 0.7 Gyr the binary can be expected to stay in the outskirts if it is currently on a highly eccentric orbit in the cluster (Colpi et al. 2002).

It turned out that archival ESO Wide Field Imager and *HST* WFPC2 images were available of the field, and those allowed us to identify the white-dwarf companion of PSR J1911–5958A (Bassa et al. 2003b; the source was also identified in new VLT observations by Ferraro et al. 2003). It is relatively bright and hot, with a best-fit temperature of ~ 11000 K. As the distance is known, we have a measure of the radius; the implied mass is low, about $0.2 M_{\odot}$, as expected from the pulsar mass function.

The high temperature implies that the white dwarf is rather young, ~ 1 Gyr, even if it has a thick hydrogen layer (at the low cluster metallicity, the critical mass is about $0.22 M_{\odot}$; Serenelli et al. 2002). This suggests that the system was formed in a simple exchange interaction with another star or binary in the core.

Independent of its formation, the system is interesting simply because it is sufficiently bright, $V \simeq 22$, to allow spectroscopy, and measure the white dwarf and neutron star masses using the procedure outlined in Sec. 3. An advantage over systems in the field is that the distance is known, which means one can measure the white-dwarf radius using the flux and temperature, and thus have a second constraint on the white-dwarf mass.

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