Part 7
Binary Systems

The White Dwarf Companions of Recycled Pulsars

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Abstract. I review what properties of the white-dwarf companions of recycled pulsars can be inferred from optical observations, and discuss how these can help us understand the characteristics and evolution of these binaries. I focus on spectroscopic observations, describing results obtained recently, and looking forward to what may come.

1. Introduction

Our understanding of the characteristics and evolution of neutron-star binaries would benefit greatly from a better grasp of the properties of the companions. For instance, for recycled pulsars with low-mass helium white dwarf companions (low-mass binary pulsars or LMBP), evolutionary theory (for a review, see Bhattacharya & Van den Heuvel 1991) predicts a relation between the orbital period and the companion mass (Rappaport et al. 1995 and references therein). So far, it has only been possible to verify this prediction for one system, PSR B1855+09, for which Kaspi et al. (1994) determined the companion mass from Shapiro delay in the pulse arrival times.

Another prediction from evolutionary theory is that the neutron star in a LMBP should have accreted up to 0.7 $M_\odot$ (e.g., Van den Heuvel & Bitzaraki 1995). Thus, if the neutron star started with the "canonical" 1.4 $M_\odot$ (for a recent census, see Van Kerkwijk et al. 1995), it would now be $\gtrsim 2\ M_\odot$. This would strongly constrain the equation of state (EOS) at supranuclear densities (e.g., Cook et al. 1994), since for softer EOS, like the one recently proposed by Brown & Bethe (1994), such a massive neutron star would collapse into a black hole. The only LMBP for which a neutron-star mass estimate is available, is (again) PSR B1855+09, for which Kaspi et al. (1994) found $M_{\rm NS} = 1.50^{+0.26}_{-0.14}\ M_\odot$ (68% confidence). As yet, the uncertainty is too high to allow one to draw a strong conclusion.

It would be of obvious interest to use direct observations of the white-dwarf companions to determine properties such as their mass. So far, due to their faintness, the observations have mostly been restricted to photometry, which allows one only to derive a temperature (by comparison with white-dwarf models, using an estimate of the surface gravity). The temperature can be used to constrain the cooling age, and such a constraint has led to one of the first indications that magnetic fields of pulsars do not decay (Kulkarni 1986). For an accurate measure, however, one also needs information about the mass, radius, and internal composition of the white dwarf.

As discussed in Sect. 2., spectroscopy of the white-dwarf companions can be used to determine masses and radii, and thus may allow one to verify the orbital-period/mass relation, and to obtain better limits on the cooling age. Furthermore, for the shorter orbital periods, one can measure the radial-velocity amplitude and determine the mass ratio. Combined with the white-dwarf mass, this determines the mass of the neutron star.

Given these possibilities, it is clearly worthwhile to try to obtain spectra of the white-dwarf companions. Unfortunately, there are not many that are bright enough, and before the 10 m Keck telescope became available, only the companion of PSR J0437−4715 was observed spectroscopically (Danziger et al. 1993). This white dwarf, however, was too cool to show any features (see Sect. 3.). Recently, we have obtained a number of spectra of other white-dwarf companions (Van Kerkwijk & Kulkarni 1995, hereafter Paper I; Van Kerkwijk et al. 1996, hereafter Paper II), which all show more interesting spectra (Sect. 3.).

2.   Measuring a White Dwarf

A number of methods have been employed to determine fundamental parameters of white dwarfs, such as their mass, radius, and luminosity. In general, if one can measure any combination of the mass and radius, one can determine the mass and radius separately using the mass-radius relation. This relation is reasonably well understood, since white dwarfs have a relatively simple structure, which, for low enough temperatures, is determined by the degeneracy of the electrons (Chandrasekhar 1939; Hamada & Salpeter 1961 for a detailed study). One can do better by using evolutionary models in which finite-temperature effects and the thickness of the surface hydrogen and/or helium layers are taken into account (see Bergeron et al. 1992). Such models have been produced by, e.g., Wood (1992, 1995). Having determined the mass and radius, the same models can be used to determine the age of the white dwarf from the temperature.

A number of different methods have been used to infer white-dwarf masses (discussed in some detail by Bergeron et al. [1992]). They are based on determinations of: (i) the radius, from accurate distance, flux and temperature estimates; (ii) the gravitational redshift, using spectroscopically determined velocity shifts between lines from the white dwarf and a reference, usually a common-proper-motion companion $(GM/Rc = 0.635(M/M_\odot)(R/R_\odot)^{-1}$ km s^{-1}); (iii) the surface gravity, determined from fitting the line profiles to model atmospheres; (iv) mode analysis of pulsating white dwarfs; and (v) the orbit for a white dwarf in a resolved binary. Of course, to this list one should add: (vi) Shapiro delay for white-dwarf, pulsar binaries in nearly edge-on orbits.

Of these, only the one using the surface gravity can be applied to a large number of objects. The model-atmosphere calculations required for this purpose are relatively straightforward, as usually only one element has to be taken into account—the elements having been separated due to the high gravity—and as the pressure is high enough for LTE to be a good approximation. The technique is furthest developed for the white dwarfs with hydrogen atmospheres (called 'DA'; for a review, Wesemael et al. 1993), and masses for a large number of DA white dwarfs have been determined (e.g., Bergeron et al. 1992).

There are a two possible problems in applying this method to the white-dwarf companions of recycled pulsars, both related to the fact that they are, in general, less massive and cooler than the white dwarfs studied so far. The lower mass implies that they have helium in their core, instead of the usual carbon and oxygen, and for these helium white dwarfs only the Hamada-Salpeter zero-temperature mass-radius relation is available. This situation should improve, however, as cooling models specifically for helium white dwarfs are being produced (Hansen & Phinney 1996; Phinney, these proceedings).

A problem related to the lower temperatures is that at $T \lesssim 12000$ K the hydrogen layer becomes convective, and helium from the core might get dredged up and mixed in. The additional pressure exerted by the helium would be very hard to distinguish from an increased surface gravity (Bergeron et al. 1991), except perhaps in the infrared (Bergeron et al. 1995). Thus, ignoring it would lead to an overestimate of the mass. Whether or not this will be a problem, depends mostly on whether the hydrogen layer is thin enough for the convection zone to reach the helium core. The best constraints, derived from asteroseismology of pulsating white dwarfs (e.g., Fontaine et al. 1994 and references therein), indicate rather thick hydrogen layers ($\sim 10^{-4}$ $M_{\rm WD}$), consistent with predictions from evolutionary models (for a review, D'Antona & Mazzitelli 1990). For such thick layers, little mixing should occur. From a comparison of spectroscopic masses with those derived from gravitational redshifts, however, it seems that for cooler temperatures the former are systematically higher than the latter, indicating that helium may in fact be present (Reid 1996).

3.   Results for Individual Systems

PSR J0437−4715   ($P = 5.76$ ms, $P_{\rm orb} = 5.74$ d; for the most recent timing results, see Bell et al. 1995) is the closest recycled pulsar known. A candidate companion was identified on the UK Schmidt sky survey by Johnston et al. (1993). This identification was confirmed in follow-up studies by Bailyn (1993), Bell et al. (1993), and Danziger et al. (1993). These authors found that the white dwarf is relatively bright and red ($V = 20.9$, $B - V = 1.3$ [note that the photometry listed in the three papers is not quite consistent]). The inferred temperature is about 4000 K. Danziger et al. (1993) found that the spectrum is featureless. This is not unexpected, since in white dwarfs both hydrogen and helium are spectroscopically invisible at ~ 4000 K.

It may be possible to constrain the surface gravity (and the abundances) somewhat from accurate optical and near-infrared photometry (see Bergeron et al. 1995). For this relatively nearby pulsar, however, a better handle on the mass can probably be obtained by determining an accurate distance (to better than 10% or so). For this system, there are four possibilities: (i) VLBI parallax; (ii) timing parallax; (iii) the proper motion combined with the velocity inferred from optical observations of the bow shock (as has been done for PSR B1957+20 by Aldcroft et al. 1992); and (iv) the proper motion combined with the apparent decay of the orbital period (Bell & Bailes 1996; Bell, these proceedings). The distance combined with the observed flux and temperature can be used to infer the radius and thus, with the mass-radius relation, the mass of the white dwarf.
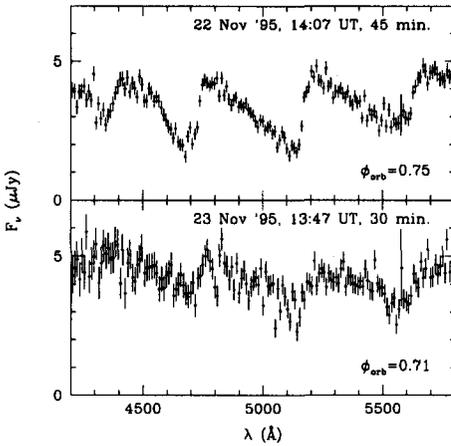
Figure 1.   Two spectra of the companion of PSR B0655+64, taken at approximately the same orbital phase. (Note that the observing conditions were not photometric. Hence, the absolute flux levels are not reliable.)   The large change in strength of the Swan C_2 bands confirms the conclusion drawn in Paper I that the changes are not related to orbital effects. From all spectra taken in November 1995, a periodicity of 9.7 ± 0.1 h is indicated.

PSR B0655+64   ($P = 196$ ms, $P_{orb} = 1.03$ d; Jones & Lyne 1988; Taylor & Dewey 1988) has, given the rather high companion mass of $\sim 0.7\ M_\odot$ indicated by the mass function, most likely been through a phase as a high-mass X-ray binary, followed by spiral in (e.g., Bhattacharya & Van den Heuvel 1991). Presumably, the helium core left was not massive enough to form a second neutron star. Such low-mass helium stars become giants (Paczynski 1971; Habets 1986), and a second stage of mass transfer may ensue. It seems likely that in this stage any remaining hydrogen will disappear. Thus, one expects to be left with a white dwarf with a carbon-oxygen core and a helium atmosphere.

The companion was identified by Kulkarni (1986). It has $V = 22.2$ and $V - R = 0.1$, indicating a temperature of about 6000 to 9000 K. First spectra were taken on New Year's Eve 1995 with the Keck telescope (Paper I). These spectra showed strong absorption bands of C_2, the so-called Swan bands (see also Fig. 1). White dwarfs showing carbon are called DQ stars, and have for a long time posed a major puzzle, since it was not understood how there could be carbon in the photosphere, when gravity should long since have separated the elements. It has become clear that it is because trace amounts of carbon are dredged up when the helium atmosphere becomes maximally convective, at $T \simeq 12000$ K (Pelletier et al. 1986). Subsequently, the carbon will only slowly be depleted from the convective helium layer. Thus, the detection of carbon in the companion directly confirms that it is a carbon-oxygen white dwarf.

Unlike what is seen in other DQ stars, the Swan bands were seen to vary in strength, by about a factor two in less than two hours (Paper I). This seems to indicate that the white dwarf has brighter and darker spots on its surface, possibly due to magnetic fields (a locally higher magnetic field strength would lead to a lower temperature—like in a sunspot—and thus to much stronger molecular bands). The change in strength was shown to be too fast and too large to be due to orbital modulation. This is confirmed by additional spectra obtain in November 1995, which show widely different band strengths at the same orbital phase (Fig. 1). Most likely, the modulation reflects the white-dwarf rotation. From the November data, a period of 9.7 ± 0.1 h is indicated.
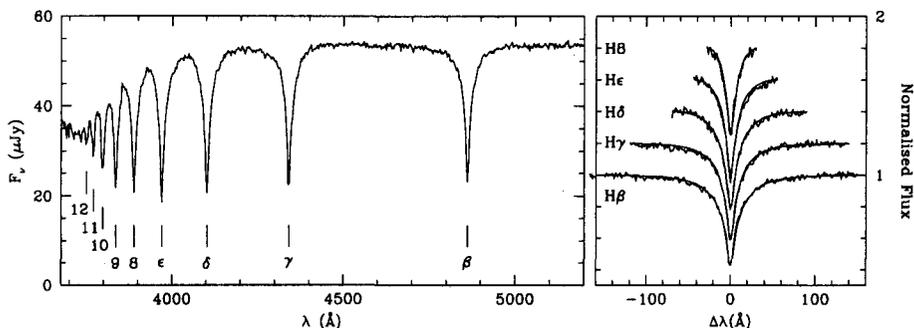
Figure 2.   The spectrum of the white-dwarf companion of PSR J1012+5307 (taken from Paper II), with the Balmer lines indicated. In the right-hand panel, the normalized profiles of Hβ to H8 are shown, with the best-fit model-atmosphere profiles superposed. The fit gives $T_{\text{eff}} = 8550 \pm 25$ K, and $\log g = 6.75 \pm 0.07$ (cgs units).

In Paper I, it was noted that if the helium-giant progenitor was filling its Roche lobe and rotating synchronously, it would have been spun up due to conservation of angular momentum when it shrunk to form a white dwarf. If the spin-up is mostly due to the angular momentum contained in the remaining giant envelope, the envelope mass must have been $\sim 10^{-4.5}$ $M_{\odot}$. Interestingly, this is similar to the helium-layer masses that are inferred using other techniques (Pelletier et al. 1986; Weidemann & Koester 1995; Dehner & Kawaler 1995).

PSR B0820+02   ($P = 865$ ms, $P_{\text{orb}} = 1232$ d; Taylor & Dewey 1988) has the longest orbital period of all LMBPs known. Thus, it provides an excellent opportunity to test the orbital-period, mass relation. Its companion was identified by Kulkarni (1986) and studied in more detail by Koester et al. (1992). It is bright enough ($V = 22.8$) for spectroscopy. A first spectrum shows that it is a DA white dwarf (Paper I), and thus a mass determination via the surface gravity will be possible (fortunately, the temperature of 14000–16500 K [Koester et al. 1992] is high enough that helium will certainly not be present.). With about one night of Keck observations, we hope to be able to do this.

PSR J1012+5307   ($P = 5.26$ ms, $P_{\text{orb}} = 0.60$ d; Lorimer et al. 1995) has a relatively bright optical counterpart ($V = 19.6$), found on the Palomar sky survey by Nicastro et al. (1995). Astrometry and photometry by Lorimer et al. (1995) confirmed the association, and showed that the white dwarf was rather hot, $T_{\text{BB}} = 9400 \pm 300$ K. This indicates a cooling age of a couple 10^8 yr, much shorter than the characteristic age of 7×10^9 yr (but see Alberts et al. 1996).
    The spectrum of the companion of PSR J1012+5307 shows hydrogen lines, from Hα up to H12 (Paper II; see Fig. 2). The presence of the higher Balmer lines indicates that the object is a low-mass white dwarf. From a model-atmosphere fit (Fig. 2), a temperature $T_{\text{eff}} = 8550 \pm 25$ K and a surface gravity $\log g = 6.75 \pm 0.07$ (cgs units) are derived. Using the Hamada-Salpeter zero-temperature relation,
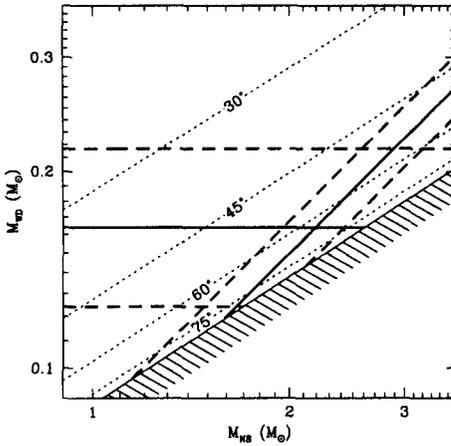
Figure 3. The masses of PSR J1012+5307 and its companion (taken from Paper II). Shown are the constraints from the pulsar mass function (thin, drawn curve for $i = 90°$; dotted curves for inclinations as indicated), the ratio of the radial-velocity amplitudes (thick, slanted curve), and the white-dwarf surface gravity (thick, horizontal curve). For the latter two, the 95% uncertainty regions are indicated by thick, dashed curves.

with an approximate finite-temperature correction, we infer a mass $M_{WD} = 0.16 \pm 0.02\,M_{\odot}$ (the lowest among all spectroscopically identified white dwarfs).

We also derive radial velocities, and find a radial-velocity amplitude $K_{WD} = 280 \pm 15$ km s^{-1} and systemic velocity $\gamma = -50 \pm 15$ km s^{-1}. The implied mass ratio is $M_{NS}/M_{WD} = 13.3 \pm 0.7$. From this mass ratio, the mass of the white dwarf, and the pulsar mass function, we find that with 95% confidence $1.5 < M_{NS}/M_{\odot} < 3.2$ (see Fig. 3).

This determination is not yet accurate enough to constrain the equation of state, or to test evolutionary theory, but it does show that further study may well prove fruitful. It will be relatively straightforward to improve the accuracy of the mass ratio, which, as is clear from Fig. 3, might already lead to an interesting constraint on the mass of the neutron star. It will be less easy to improve the white-dwarf mass estimate. This is because of the uncertainties in the mass-radius relation for these very low-mass white dwarfs, and because of the possible presence of helium in the atmosphere. As discussed above, if helium is present, the true surface gravity—and thus the inferred mass—will be lower.

The pulsar is relatively nearby and bright, however, and it may well be possible to derive an accurate distance. This would allow one to obtain a direct estimate of the radius. If this is the same as the predicted one ($0.028\pm0.002\,R_{\odot}$), it would give confidence in the result. If it is not, one can either assume there is a problem with the mass-radius relation, but not with helium pollution, and infer a mass from the radius in combination with the observed surface gravity, or one can assume that there is helium pollution, but that the mass-radius relation is fine, and use that to derive a mass from the radius. Another possibility is to search carefully for Shapiro delay in the pulse arrival times. As one can see from Fig. 3, the inclination should be $\gtrsim 60°$ for $M_{NS} \lesssim 2\,M_{\odot}$.

4.   Plans and Conclusions

Two other white-dwarf companions, of PSR J1022+1001 (Camilo 1995) and of PSR J0218+4232 (Navarro et al. 1995), are bright enough for spectroscopy.

For the former, the mass function indicates a massive white dwarf, like for PSR B0655+64, and one might hope to find a similarly interesting spectrum. We have identified the companion using the 5 m Hale telescope (see also Lundgren, these proceedings), and it is of similar brightness and temperature as PSR B0655+64. If Swan bands are present too, and our ideas about the cause of the variations are correct, any periodicity should be faster than in PSR B0655+64. For PSR J0218+4232, we have found an optical counterpart on Keck images. With an orbital period of 2 days, it may be possible to do a radial-velocity study like for PSR J1012+5307.

A conclusion could be that from binary pulsars one still can hope to learn sometimes not quite as much as expected, sometimes more, and sometimes the unexpected. Combining radio observations of the pulsar with optical observations the white dwarf, one may hope to overdetermine the system, so that the consistency of the results can be verified (like from timing alone for the double neutron-star binaries). At present, perhaps the most promising system is PSR J1012+5307, for which we found tantalizing indications for a neutron star that is truly more massive than 1.4 $M_\odot$. It seems worthwhile to do an in-depth study of this system, using further optical radial-velocity measurements to refine the mass ratio, radio VLBI and timing to determine the distance, and searches for Shapiro delay to constrain the companion mass and inclination. Higher-order effects in the timing might help constrain the inclination, as could perhaps the orbital variation of the scintillation velocity (see Lyne 1984). For this system, as well as the others, the coming years should prove interesting.

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