SPECTROSCOPY OF THE WHITE DWARF COMpanions OF PSR 0655+64 AND PSR 0820+02

M. H. Van KerkwijK and S. R. Kulkarni
Palomar Observatory, California Institute of Technology 105-24, Pasadena, CA 91125
Received 1995 May 29; accepted 1995 September 14

ABSTRACT

We present spectra of the white dwarf companions of the radio pulsars 0655+64 and 0820+02. For the latter, we find a spectrum showing strong lines of hydrogen, i.e., that of a DA star. From modeling these lines, the mass of a white dwarf can, in principle, be determined accurately, thus leading to constraints on the evolution of the binary and the mass of the neutron star. Our present spectrum is not of sufficient quality to set a strong limit, but it does indicate that the white dwarf most likely has a low mass. This is consistent with the star being a helium white dwarf, as would be expected from considerations of the mass function and the preceding evolution. From similar considerations, the companion of PSR 0655+64 is expected to be a more massive, carbon-oxygen white dwarf. This is confirmed by our spectra, which show the Swan bands of molecular carbon, making it a DO star. Unlike what is observed in other DQ stars, the strength of the Swan C$_2$ bands changes drastically, by a factor of 2 in ~2 hr. We suggest this reflects large-scale surface inhomogeneities that are rotated in and out of the observed hemisphere. If so, this would imply that the white dwarf rotates supersynchronously.

Subject headings: stars: individual (PSR 0655+64, PSR 0820+02) — stars: neutron — white dwarfs

1. INTRODUCTION

About one-twentieth of the known radio pulsars reside in a binary system. Two have massive, early-type companions and have properties rather similar to the average isolated radio pulsar. These presumably have evolved companions—either white dwarfs or neutron stars—and differ markedly from (most of) their isolated counterparts, showing more rapid spin periods and smaller magnetic fields (for recent reviews, see Bhattacharya & van den Heuvel 1991; Verbunt 1993; Phinney & Kulkarni 1994; Kulkarni 1995; these references have been used throughout this section). The rapid spin is generally believed to result from a phase of mass transfer in the evolutionary history of the binary, during which a large amount of mass and angular momentum is accreted. The reduction of the magnetic field is thought to occur in this phase as well, but the physical mechanism underlying this (e.g., it being “buried” by the accreted matter) is not understood.

The radio pulsars with evolved companions can be divided into three groups, generally referred to as the low-, intermediate-, and high-mass binary pulsars (hereafter LMBP, IMBP, and HMBP, respectively). While these classifications are made on the basis of the inferred mass of the companion (from the mass function), stellar evolutionary scenarios allow us to relate these systems to the descendents of binaries composed of a neutron star and a low-mass ($M \lesssim 1 M_\odot$), intermediate-mass ($1 M_\odot \lesssim M \lesssim 8 M_\odot$), and high-mass ($M \gtrsim 8 M_\odot$) secondary, respectively. The expectation is that these secondaries evolve to helium white dwarfs, carbon-oxygen (C-O) white dwarfs, and neutron stars, respectively. There is a fairly systematic trend of decrease in magnetic field strength as one proceeds from HMBPs to LMBPs. Presumably, this reflects the decrease in speed with which evolution proceeds in these systems and the corresponding increase of the total amount of matter that is accreted.

Observations of the white dwarf companions provide a number of diagnostics for these objects. For instance, the surface temperature of the white dwarf can be used to infer a cooling age, which sets a lower limit to the age of the neutron star. Such limits have been derived from broadband photometry for PSR 0655+64 (Kulkarni 1986), 0820+02 (Kulkarni 1986; Koester, Churngman, & Reimers 1992), 1855+09 (Cal-lanan et al. 1989; Kulkarni, Djorgovski, & Klemola 1991), J0437–4715 (Bailyn 1993; Bell, Bails, & Bessel 1993; Danziger, Baade, & Della Valle 1993), and J1012+5307 (Lorimer et al. 1995), and they provide the strongest evidence so far that magnetic fields of neutron stars do not decay on a timescale of millions of years, as had been thought before. In the absence of good constraints on the masses of the white dwarfs, however, the cooling ages cannot be very accurately determined.

Mass determinations would not only lead to better constraints on the cooling ages but also allow one to verify, e.g., the orbital period, white dwarf mass relation predicted for the LMBP (Refsdal & Weigert 1971; Savonije 1987; Joss, Rappaport, & Lewis 1987; Rappaport et al. 1995) or to constrain the mass of the neutron star. In addition, they could be used to obtain independent distance estimates to the systems, which can be compared to those derived from the dispersion measure of the pulsar.

Constraints on the white dwarf mass can be derived from Shapiro delay, but this is possible for only a few binaries with favorable geometries. Another possibility is to use spectroscopy of the white dwarfs. In recent years, much progress has been made in the spectroscopic determination of surface gravities (and hence masses and radii), especially for white dwarfs of spectral type DA, i.e., those with a hydrogen atmosphere (e.g., Bergeron, Saffer, & Liebert 1992). Spectroscopy of the very faint companions of binary pulsars is non-trivial and has so far only been attempted for the brightest, that of PSR J0437–4715 (Danziger et al. 1993). Unfortu-

---

1 Based on observations obtained at the W. M. Keck Observatory on Mauna Kea, Hawaii, which is operated jointly by the California Institute of Technology and the University of California.
nately, that white dwarf is rather cool \( T \approx 4000 \) K, and no line features were detected.

Here we present spectroscopy of two somewhat fainter, but hotter companions, one of an IMBP, PSR 0655+64, and one of a LMBP, PSR 0820+02. For recent radio studies of these binaries, see Taylor & Dewey (1988) and Jones & Lyne (1988). For previous optical studies, see the references listed above.

2. OBSERVATIONS

Spectra were taken on New Year’s Eve of 1995 at the Keck 10 m telescope with the Low-Resolution Imaging Spectrometer (LRIS). With the 300 line mm\(^{-1}\) grating, the wavelength range of 3750–8780 Å was covered at 2.5 Å pixel\(^{-1}\). The observing conditions were good throughout the night, but a substantial amount of time was lost due to telescope problems.

Three spectra were taken of the companion of PSR 0655+64 \((V = 22.2 \) mag\), starting at 1995 January 1, 8:54, 9:56, and 10:16 UT, with integration times of 30, 15, and 45 minutes, respectively. For the first spectrum, the slit was positioned over the companion and a nearby elliptical galaxy (see Kulkarni 1986), while for the latter two it was set close to the parallactic angle. A 0′′7 wide slit was used, giving a resolution of \( \sim 8 \) Å. The companion of PSR 0820+02 \((V = 22.8 \) mag\) was observed for 45 minutes starting at 14:26 UT, using a 1′′ slit to improve the throughput (leading to a resolution of \( \sim 12 \) Å). For approximate flux calibration, the spectrophotometric standard HD 84937 (Oke & Gunn 1983) was observed.

The reduction of all spectra was done using MIDAS\(^2\) and programs running in the MIDAS environment. The frames were bias-corrected, flat-fielded, and sky-subtracted using standard procedures. The spectra were extracted using an optimal-extraction method similar to that presented by Horne (1986). It turned out that the different exposures of the flux standard were inconsistent in both level and slope of the continuum. Since flux calibration was thus impossible, we normalized the spectra for the representation shown here (Fig. 1). This was done by dividing by a continuum defined by one of the flux-standard spectra and scaling by \( \lambda^\beta \), with \( \beta \) chosen such that the continuum appeared straight.

3. RESULTS AND DISCUSSION

3.1. PSR 0655+64

The spectra of the companion of PSR 0655+64 (Fig. 1) are those of a DQ star, showing strong Swan C\(_2\) bands (for a

\(^2\) The Munich Image Data Analysis System is developed and maintained by the European Southern Observatory.
review of white dwarf spectra, see Wesemael et al. 1993). The Swan C\textsubscript{2} bands are thought to be due to traces of carbon in a helium-rich atmosphere, brought up by convection from a deeper region, which is enriched in carbon due to upward diffusion of carbon from the core (Pelletier et al. 1986). Thus, the presence of the Swan bands directly confirms the expectation that the object is a carbon-oxygen white dwarf.

The presence of the Swan bands, combined with the absence of lines from atomic carbon, also indicates that the temperature is between 6000 and 9000 K (inferred from Wegner & Yakovich 1984 and Wesemael et al. 1993). This compares well with the range of 5500–8000 K derived from photometry of this star (Kulkarni 1986) and hence provides independent confirmation of the conclusion of Kulkarni (1986) that the cooling age of the white dwarf is \( \approx 2 \times 10^7 \) yr, comparable to the characteristic age of \( P/2 \approx P = 3.6 \times 10^3 \) yr of the pulsar.

From the three spectra that we have, one can see that the strength of the C\textsubscript{2} features is variable. In fact, the total equivalent width changes by a factor of 2 over the 2 hr spanned by the observations, from \( \approx 170 \) to \( \approx 330 \) \AA\ in the range 4430–5650 \AA. As far as we know, this is unprecedented. Since white dwarfs in general are not particularly variable stars, it is tempting to relate the changes to fixed surface patterns—due to, e.g., abundance or temperature variations, perhaps related to the presence of a magnetic field as in magnetic Ap stars (Borra, Landstreet, & Mestel 1982)—that are rotated in and out of the observed hemisphere. If so, then from the swiftness of the change in the spectrum, the strength of the features, and the integration times, it is easy to see that a possible periodicity cannot be shorter than \( \approx 3 \) hr (otherwise, the changes would be washed out) or longer than \( \approx 12 \) hr (to allow a change from \( \approx 30\% \) to \( \approx 70\% \) depth of the strongest part of the absorption).

This is substantially shorter than the \( \approx 1 \) day orbital period, and thus an association with orbital variations—such as could be produced by, e.g., heating of one hemisphere—seems unlikely.

If we associate the variations with the rotation of the white dwarf, then its rotation period has to be 2–8 times shorter than the orbital one. This might actually not be unexpected: the progenitor of the white dwarf was a helium giant transferring mass to the pulsar (e.g., Iben & Tutukov 1993), and if it was rotating synchronously—as does not seem implausible given the extremely circular orbit (\( e = 7.5 \times 10^{-5} \); Jones & Lyne 1988)—then it would have been spun up due to conservation of angular momentum when it shrank to form a white dwarf. In fact, we can set a rough upper limit to the mass of the envelope that fell back onto the white dwarf if we assume that the effect due to the shrinking of the core can be neglected. For this case, the moment of inertia in the envelope has to be at least equal that of the core—or equivalently (by assumption) that of the white dwarf—in order to be able to spin it up by at least a factor of 2. Hence, the mass of the envelope should be \( \approx M_{\text{env}} R_{\text{WD}}^2/\rho_{\text{env}} \) (ignoring differences in structure).

Since the progenitor was filling its Roche lobe, \( R_{\text{en}} \approx R_L \approx (GM_{\text{WD}}/10\Omega_M^2)^{1/3} \approx 2 R_{\text{WD}} \) (using eq. [10.1] of Phinney & Kulkarni 1994). With \( M_{\text{WD}} \approx 0.8 \, M_\odot \) and \( R_{\text{WD}} = 0.01 \, R_\odot \), one finds a mass of the envelope of a few times \( 10^{-4} \, M_\odot \). Interestingly, this is similar to the mass of the helium envelope that is inferred for DQ stars from the presence and strength of the carbon features (Pelletier et al. 1986; but see also Weideman & Koester 1995; Dehner & Kawaler 1995).

While we realize that our estimate is a rough one—the very existence of a periodicity still needs to be confirmed—we note that, in principle, it might be possible to use rotation periods of white dwarfs in similar systems to constrain the final phases of the evolution. Especially for the systems with somewhat longer orbital periods in which the angular momentum is dominated by the envelope, the final spin rate should depend almost uniquely on the radius of the giant. Since the latter is related to the orbital period, one might expect, e.g., to find a correlation between the spin period and orbital period in such systems.

### 3.2. PSR 0820+02

In contrast to the companion of PSR 0655+64, this white dwarf shows strong lines of hydrogen (see Fig. 1), making it a DA white dwarf. As mentioned in § 1, for a DA white dwarf it is possible to determine surface temperature and gravity uniquely from the spectrum. From a first comparison of the spectrum with model atmospheres, kindly done for us by P. Bergeron, it follows that it is consistent with the temperature being in the range of 14,000–16,500 K found by Koester et al. (1992). The best-fitting surface gravities for that range would indicate a mass of \( 0.25–0.35 \, M_\odot \), consistent with the idea that it is a helium white dwarf. However, the spectrum is of insufficient quality to set a strong limit: the 95\% upper limit to the mass is \( \approx 0.9 \, M_\odot \). Thus, it is not yet possible to verify whether the mass is within the range of 0.42–0.60 \( M_\odot \) expected from the orbital period, white dwarf mass relation (Rappaport et al. 1995).

From photometry, combined with an upper limit of 1.9 kpc to the distance, Koester et al. (1992) derived a lower limit of \( 0.5 \, M_\odot \) to the mass of the companion of PSR 0820+02. Indeed, if the white dwarf were to have a mass of \( 0.3 \, M_\odot \), it would have \( M_\odot \approx 10.4 \) mag (P. Bergeron, private communication), and with \( V \approx 22.8 \) mag and \( A_V \approx 0.1 \) mag (Koester et al. 1992), the system would be at a distance of \( \approx 2.8 \) kpc. We note, however, that the distance limit Koester et al. used was derived by taking twice the distance of 0.95 kpc indicated by the dispersion measure of 23.6(2) cm\(^{-3}\) pc (Taylor & Dewey 1988) combined with the model of the Galactic electron distribution of Lyne, Manchester, & Taylor (1985). With the more recent model of Taylor & Cordes (1993), one would infer a distance of 1.4 kpc. Taylor & Cordes estimate that the mean uncertainty in the new dispersion-measure derived distances is \( \approx 25\% \), but they note that there is a dependence on the position of the pulsar. For PSR 0820+02, at \( l = 222^\circ \), \( b = 21^\circ \), we find from their Figures 7 and 8 that the model is substantially more uncertain.

While it is thus at present not possible to constrain the mass unambiguously, we note that for a 0.6 \( M_\odot \) white dwarf, Koester et al. (1992) derived that the cooling age was within an “allowed range” of 1.5–2.7 \( \times 10^8 \) yr, which seems only marginally consistent with the characteristic age of 1.1 \( \times 10^9 \) yr of the neutron star (which should be an upper limit to the true age). If the white dwarf were to have a lower mass, the two age estimates would be in better agreement.

### 4. CONCLUSIONS

We have presented spectra of the white dwarf companions of the radio pulsars 0655+64 and 0820+02. From these spectra, combined with published temperature determinations, we can classify the two as DQ6-9 and DA3/4, respectively. This confirms the expectation that the former is a
carbon-oxygen white dwarf and is consistent with the latter being a helium white dwarf.

As we had hoped, it will be possible to derive accurate temperatures and surface gravities for the companion of PSR 0820+02. While this will likely be difficult for the companion of PSR 0655+64, its changing spectrum may instead turn out to provide us with a unique possibility to learn more about its previous evolution, as well as about the formation of spectral features in white dwarfs. It seems clear that further spectral studies of both these and other pulsar companions are warranted.

We are very grateful to Pierre Bergeron for making the model-atmosphere comparisons, and we thank him, Brad Hansen, Yanqin Wu, and Peter Goldreich for useful discussions. M. H. v. K. is supported by a NASA Hubble Fellowship and S. R. K. by grants from the US NSF, NASA, and the Packard Foundation.

REFERENCES

Bailyn, C. D. 1993, ApJ, 411, L83
Bell, J. F., Bailes, M., & Bessell, M. S. 1993, Nature, 364, 603
Bergeron, P., Saffer, R. A., & Liebert, J. 1992, ApJ, 394, 228
Bhattacharya, D., & van den Heuvel, E. P. J. 1991, Phys. Rep., 203, 1
Borra, E. F., Landstreet, J. D., & Morel, L. 1982, ARA&A, 20, 191
Callanan, P. J., et al. 1989, MNRAS, 238, 25P
Danziger, I. J., Baade, D., & Della Valle, M. 1993, A&A, 276, 382
Dehner, B. T., Kawaler, S. D. 1995, ApJ, 445, L141
Horne, K. 1986, PASP 98, 609
Iben, I., Jr., & Tutukov, A. V. 1993, ApJ, 418, 343
Jones, A. W., & Lyne, A. G. 1988, MNRAS, 233, 473
Joss, P. C., Rappaport, S., & Lewis, W. 1987, ApJ, 319, 180
Koester, D., Channugan, G., & Reimers, D. 1992, ApJ, 395, L107
Kulkarni, S. R. 1986, ApJ, 306, L85
———. 1995, in ASP Conf. Ser., Vol. 72, Millisecond Pulsars: A Decade of Surprise, ed. A. S. Fruchter, M. Tavani, & D. C. Backer (San Francisco: CA), 79
Kulkarni, S. R., Djorgovski, S., & Klemola, A. R. 1991, ApJ, 367, 221
Lorimer, D. R., Lyne, A. G., Festin, L., & Nicastro, L. 1995, Nature, 376, 393
Lyne, A. G., Manchester, R. N., & Taylor, J. H. 1985, MNRAS, 213, 613
Oke, J. B., & Gunn, J. E. 1983, ApJ, 266, 713
Pelletier, C., Fontaine, G., Wesemael, F., Michaud, G., & Wegner, G. 1986, ApJ, 307, 242
Phinney, E. S., & Kulkarni, S. R. 1994, ARA&A, 32, 591
Rappaport, S., Podsiadlowski, Ph., Joss, P. C.,, Di Stefano, R., & Han, Z. 1995, MNRAS, 273, 731
Refsdal, S., & Weigert, A. 1971, A&A, 13, 367
Savonije, G. J. 1987, Nature, 325, 416
Taylor, J. H., & Cordes, J. M. 1993, ApJ, 411, 674
Taylor, J. H., & Dewey, R. J. 1988, ApJ, 332, 770
Verbunt, F. 1993, ARA&A, 31, 93
Wegner, G., & Yackovich, F. H. 1984, ApJ, 284, 257
Weidemann, V., & Koester, D. 1995, A&A, 297, 216
Wesemael, F., Greenstein, J. L., Liebert, J., Lamontagne, R., Fontaine, G., Bergeron, P., & Glaspey, J. W. 1993, PASP, 105, 761