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Letter to the Editor

The white dwarf companion to PSR B0820+02*

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Abstract. We report new spectroscopic and photometric observations of the white dwarf companion to the pulsar PSR B0820+02. The white dwarf is a normal DA white dwarf with an effective temperature of 15000 K and a mass of $0.6\ M_\odot$. The mass and orbital period of this system confirm recent simulations of the evolution of a neutron star – main sequence binary with mass exchange and thus implicitely theoretical predictions of the dependence of the red giant radius on the He-core mass. The cooling age of the white dwarf is larger than the spin-down age of the pulsar, unless a braking index of 2.2 is assumed.

Key words: stars: pulsars: individual: PSR B0820+02 – stars: white dwarfs

1. Introduction

About 40 millisecond pulsars are known as members in binary systems outside of Globular Clusters. Their properties are significantly different from those of normal pulsars: spin periods are shorter, $P \leq 100$ ms in most cases, and the magnetic fields are smaller, in the range $10^8 - 10^{11}$ G. The mass function and in very few cases direct evidence suggest that the companion is usually a low mass He-core white dwarf with $M = 0.15$–$0.25\ M_\odot$, although very recently several more were discovered with higher mass companions and probably C/O cores.

The most widely accepted scenario for the formation of these systems involves the following stages (see e.g. the reviews by Bhattacharaya and van den Heuvel 1991; Bhattacharaya 1995; Phinney and Kulkarni 1994; Lyne and Graham-Smith 1998):

- A primary with $M > 8\ M_\odot$ in a main sequence (MS) binary evolves to supernova explosion and leaves a neutron star.
- Later, the secondary evolves, leading to mass transfer by Roche lobe overflow. The transfer of angular momentum spins up the neutron star to millisecond periods (hence the name “recycled pulsar”).
- The magnetic field possibly decreases during the accretion by some not well understood process (Taam and van den Heuvel 1986).
- The outer layers of the secondary are lost before the He core can evolve to the necessary mass for He ignition ($\sim 0.45\ M_\odot$).
- After the end of the mass transfer phase the secondary evolves to a low mass He-core white dwarf and the spin of the neutron star slows down.

An alternative scenario has the primary (with mass below $8\ M_\odot$) evolve first into a white dwarf and then, after accretion from the secondary brings it over the Chandrasekhar limit, to collapse to a neutron star (NS) via “accretion induced collapse”. The following evolution of the secondary is the same as in the standard scenario. Both scenarios predict that the neutron star should be older than the white dwarf in the system. More specifically, since the end of the accretion phase means the start of the cooling of the white dwarf as well as the start for the spin-down of the neutron star, these two ages (WD cooling time and NS spin-down age) should be approximately equal.

The study of the white dwarf thus opens up a possibility for an independent age estimate, if the effective temperature, the mass, and hence the cooling age can be determined with sufficient accuracy. In addition, if the radial velocity curve of the white dwarf can be determined, an independent mass estimate for the neutron star is possible. This would allow important tests, e.g. of any relation between accreted mass and magnetic field decay (Taam and van den Heuvel 1986; Romani 1993; Wijers 1997), as well as of the equation of state for nuclear matter. The accurate determination of the white dwarf mass can also be used to test the claimed relation between the secondary mass and the orbital period of these systems (Rappaport et al. 1995). This relation is a direct consequence of the red giant radius – core mass relation as originally predicted by Refsdal and Weigert (1971), and its confirmation is therefore also a test for our theoretical understanding of stellar evolution on the giant branch.

2. Observing the white dwarf companions

Only one known companion is brighter than $V = 20$, but most are at $V = 25$ or fainter. Large telescopes are therefore neces-

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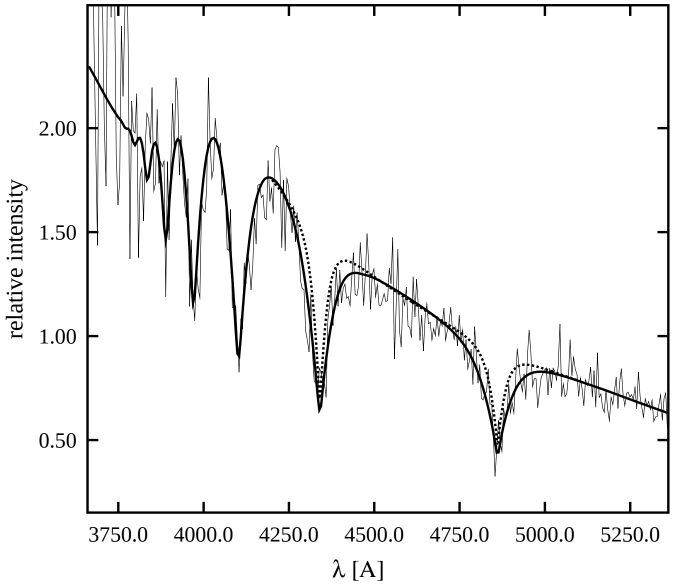

Fig. 1. Summed spectrum of the DA white dwarf companion (thin line) and the best fitting model atmosphere for $T_{\rm eff}$= 15000 K, $\log g$= 7.98. The dotted line shows some Balmer lines for a model of 19000 K and $\log g$= 7.0 as suggested by the photometric solution (see text).

sary to detect these companions and obtain spectra with sufficient S/N for a spectroscopic analysis. Early identifications and photometric observations were obtained by Kulkarni (1986), Koester et al. (1992), Bell et al. (1993), Bailyn (1993), Bell et al. (1995), Lorimer et al. (1995), Lundgren et al. (1996). Spectroscopy was successful only for the brightest objects (Danziger et al. 1993; van Kerkwijk and Kulkarni 1995; Callanan et al. 1998), but recently significant progress was achieved through the work by van Kerkwijk and collaborators (van Kerkwijk et al. 1996; van Kerkwijk and Kulkarni 1999; van Kerkwijk et al. 2000). The comprehensive study by Hansen and Phinney (1998) has demonstrated, which conclusions can be drawn from these observations.

The binary pulsar PSR B0820+02 is at the extreme end of its class with a very long orbital period of 1232.5 d, spin period $P = 864.8$ ms, and derivative $\dot{P} = 1.039\,10^{-16}$. The magnetic field is likewise unusually large for this class at $B = 3\,10^{11}$ G. The mass function $f = 0.00301$ sets a lower limit for the companion mass at $M > 0.2\ M_{\odot}$, if $1.4\ M_{\odot}$ is assumed for the primary.

The companion to PSR B0820+02 was identified in the optical range by Kulkarni (1986). Koester et al. (1992) obtained BVR photometry at the 3.6m telescope of ESO/La Silla, and concluded that the effective temperature of the white dwarf is about 15000 K, leading to a cooling age larger than the characteristic age of the pulsar. Several assumptions had to be made, however, to arrive at this conclusion, the most important among them that the white dwarf has a hydrogen-rich (DA) atmosphere and a "normal" DA mass of 0.6 $M_{\odot}$. The first assumption was finally justified when van Kerkwijk and Kulkarni (1995) obtained a spectrum using the Keck telescope, which clearly showed broad Balmer lines, although the S/N was not adequate for a detailed spectroscopic analysis.

We have therefore obtained new observations (low resolution spectroscopy and UBV photometry) on February 2, 2000 at ESO/Paranal with the VLT Unit 1 and the FORS 1 instrument. During that night, which was photometric but with a seeing changing from 1.4″ in the beginning to 0.6″ at the end, we obtained four spectra of one hour exposure time each. The last two were of much higher S/N due to the improved seeing, and we have used only these two for the combined final spectrum in Fig. 1. The spectrum was fitted using our standard grid of DA model atmospheres and a χ^2 fitting technique, with the resulting parameters $T_{\rm eff} = 15000 \pm 800$ K, $\log g = 7.98 \pm 0.13$. The corresponding theoretical spectrum is also shown in Fig. 1 (thick continuous line).

Using the evolutionary mass-radius relation of Wood (1995) we can derive a mass $M = 0.60 \pm 0.08\ M_{\odot}$, absolute magnitude $M_V = 11.28 \pm 0.10$ and a cooling age $2.21 \pm 0.11\ 10^8$ yrs.

During the same night we have also obtained several direct images of the pulsar field through U, B, and V filters. The Landolt standard fields PG 0231+051 and PG 0942-029 were observed at similar airmass and used for the transformation to the standard color system. We used the transformation equations suggested on the Paranal webpage, which include color terms. Constant values were used for these terms as well as average values for the extinction; only the zeropoints were considered free and determined from the standards. The results for the companion are $V = 22.832 \pm 0.055(0.053), B - V = -0.036 \pm 0.070(0.066), U - B = -0.744 \pm 0.083(0.76)$; the errors include the errors of the zeropoints and the values in brackets are errors from the photometry only. The typical residuals of the standards were below 0.015 for U and V, but 0.03 for B, indicating that the transparancy was probably not completely constant during the night.

A number of stars in the field was measured as an aid in transforming between images with different exposure times. The left panel in Fig. 2 shows the positions of these stars and the white dwarf. Also shown are the position of the main sequence from Cox (2000) and theoretical colors determined from our model atmosphere grid for DA white dwarfs. Assuming that the red stars are main sequence objects, we can estimate their absolute magnitude and the distance from the distance modulus $V - M_V$. The larger circles indicate those stars, which seem to be at approximately the distance of the pulsar (see below), and they seem indeed to form a well defined lower main sequence slightly shifted because of interstellar reddening. Using the direction of the reddening vector in the UBV two-color diagram, we estimate $E(B-V) = 0.1 \pm 0.05$ (three short straight lines in the figure). Because the pulsar is beyond the central dust lane this can be compared to the total extinction in that direction, which is 0.054 ± 0.009 according to Schlegel et al. (1998). We adopt $E(B-V) = 0.07 \pm 0.03$ as a conservative estime, which includes both values.

The right panel in Fig. 2 shows an enlargement of the white dwarf region of the two-color diagram with lines of constant gravity (continuous) and constant temperature (dotted) indi-

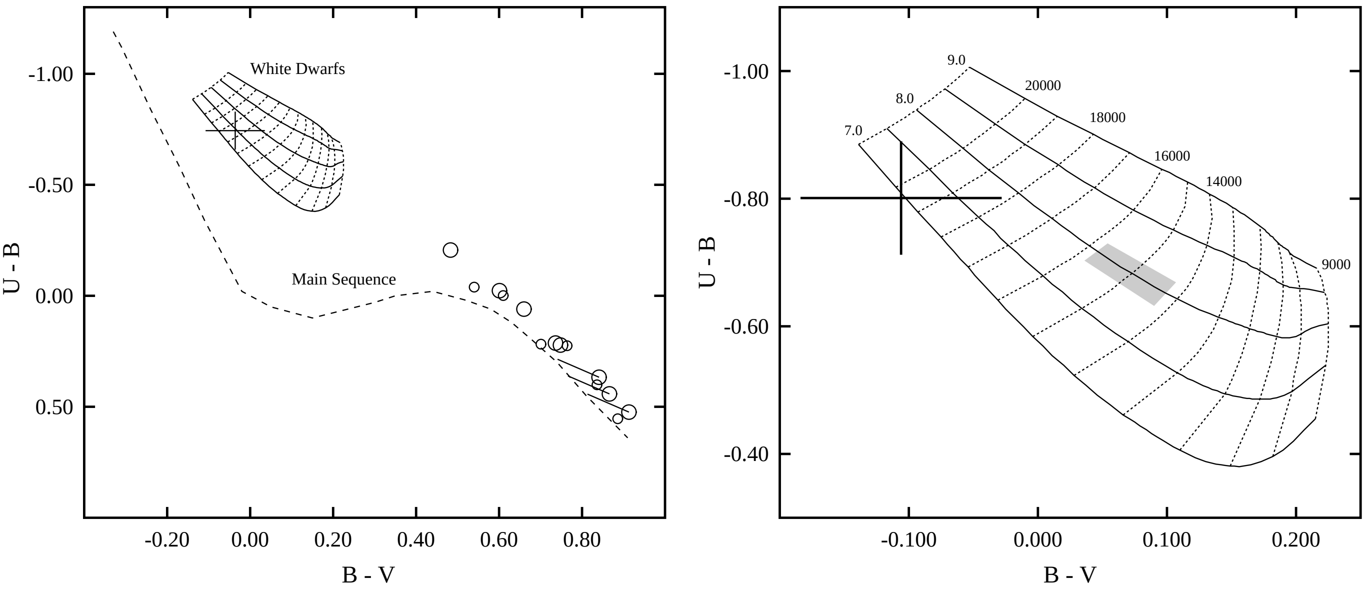

Fig. 2. Left: UBV two-color diagram with the position of the main sequence and theoretical colors for white dwarfs indicated. The cross is the pulsar companion, circles are other stars in the field close to the pulsar position. Large circles are approximately at the distance of the pulsar, if they are assumed to be main sequence stars. The line segments indicate a reddening of $E(B-V)=0.1$. Right: The white dwarf range of the two-color diagram with the dereddened position of the companion (large cross with errorbars). The shaded area is the range compatible with the spectroscopically determined parameters. Lines of constant effective temperature (dotted) and gravity (continuous) are shown and the parameters indicated by the small numbers

cated by the small numbers. The large cross is the dereddened position for the white dwarf companion, and the shaded area corresponds to the spectroscopic parameter determination. Although the colors of the companion fall into the region of the DA white dwarfs, they disagree with the spectroscopic result approximately at the 2 σ level. The small surface gravity implied by the colors can certainly be ruled out by the result of the spectral analysis as shown in Fig. 1, where several theoretical line profiles for this solution (19000 K, $\log g$=7.0) have been plotted for comparison. Considering the uncertainties (especially of the U and B magnitudes), the difficulties of transforming between theoretical models and observed colors, and the uncertainty of the reddening, we believe that the spectroscopic determination is more reliable in this case, and we will use that result together with the V magnitude in the further analysis.

3. Discussion and conclusions

The pulsar distance from the dispersion measure is $d_P = 1430$ pc with a large uncertainty allowing a range of at least 860–1790 pc (Taylor & Cordes 1993). The distance of the white dwarf companion as estimated from the distance modulus (corrected for reddening) is $d_{WD} = 1855$ pc, with a range of 1735–1983 pc, thus providing much tighter constraints on the distance of the system. If we again assume a primary mass of $1.4\,M_\odot$ and $0.6\,M_\odot$ for the secondary, the orbital inclination i is $22.5°$ and the separation 0.85 AU.

How do the age estimates of both stars compare? The equation for the *spin down age* t_P of a pulsar is (see e.g. Hansen and Phinney 1998 for a good discussion)

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

with initial period P_0, and braking index n. With the usual assumptions of $P_0 \ll P$ and $n=3$ for braking by magnetic dipole radiation the *characteristic age* for PSR B0820+02 is obtained as

$$t_{ch} = \frac{P}{2\dot{P}} = 1.3\,10^8 \text{ yrs.}$$

This is significantly lower than the cooling age of the white dwarf, and would contradict the standard scenario as outlined in the introduction. There are several possible solutions to this dilemma.

Tauris and Sennels (2000) have recently discussed a scenario for PSR B2303+46, in which the white dwarf is formed first. The most likely outcome of this scenario is, however, a system with orbital period of a few days and relatively high eccentricity, both of which are not true for PSR B0820+02. A more plausible alternative might be that the braking index n is smaller than 3. The index n is not known independently for any millisecond pulsar. However, for some young pulsars values from 2.0–2.8 are found (Lyne 1996), and Hansen and Phinney (1998) use a possible range of 2–3 in their study. If we assume n to be a free parameter the two ages would be equal for $n = 2.2$. We note in passing that any magnetic field decay during the spin-down time of the pulsar would make the real age of the pulsar even shorter and the discrepancy with the cooling age larger. This adds another piece of information to the growing evidence that the magnetic fields in recycled pulsars do not decay on time scales of the order of their characteristic ages.

Summarizing the conclusions from these new observations

- the companion to PSR B0820+02 is a normal DA white dwarf with $0.6\ M_{\odot}, T_{\rm eff} = 15000$ K
- this is only the second spectroscopically confirmed DA companion, and the first with "normal" mass and a C/O interior
- the distance from the distance modulus is consistent with that from the dispersion measure, but much more accurate
- the ages can only be made consistent, if we assume a braking index of 2.2, within the range inferred from direct measurements for some young pulsars ($n = 2$–2.8)

Tauris and Savonije (1999) and Tauris et al. (2000, THS) have recently presented extensive simulations of the evolution leading to binary millisecond pulsars, with the essential parameters being the mass of the secondary (donor) star and the initial orbital period of the neutron star - main sequence binary. Fig. 2 in THS shows a branch in the final orbital period versus white dwarf mass for donor star masses of 1.0–$1.8\ M_{\odot}$, which leads in most cases to low mass He core white dwarfs. However, if the initial period is longer than 150 d, the result can be a normal C/O core white dwarf, and the companion to PSR B0820+02 fits exactly on the high mass end of this branch. With a mass of $0.6\ M_{\odot}$ the PSR B0820+02 companion also fits very nicely the predicted M_{WD} – orbital period relation (e.g. Fig. 3 in Rappaport et al. 1995), whereas the low-mass He core solution from the photometry would be impossible to understand in this context. This relation depends — through the mass transfer rate — on the evolution of the radius of the giant donor star with the core mass. As first noted by Refsdal and Weigert (1971) the stellar parameters (luminosity, $T_{\rm eff}$, and radius) are a function only of the core He mass and independent of the details of the mass loss. Our results for the PSR B0820+02 system strongly confirm this theoretical prediction.

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