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The mass of the neutron star in the binary millisecond pulsar PSR J1012 + 5307

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ABSTRACT

We have measured the radial velocity variation of the white dwarf secondary in the binary system containing the millisecond pulsar PSR J1012 + 5307. Combined with the orbital parameters of the radio pulsar, we infer a mass ratio q ($\equiv M_1/M_2$) = 10.5 ± 0.5. Our optical spectroscopy has also allowed us to determine the mass of the white dwarf companion by fitting the spectrum to a grid of DA model atmospheres: we estimate $M_2 = 0.16 \pm 0.02\,\mathrm{M}_\odot$, and hence the mass of the neutron star is $1.64 \pm 0.22\,\mathrm{M}_\odot$, where the error is dominated by that of M_2. The orbital inclination is 52 ± 4 deg. For an initial neutron star mass of $\sim 1.4\,\mathrm{M}_\odot$, only a few tenths of a solar mass at most has been successfully accreted over the lifetime of the progenitor low-mass X-ray binary. If the initial mass of the secondary was $\sim 1\,\mathrm{M}_\odot$, our result suggests that the mass transfer may have been non-conservative.

Key words: stars: binaries: general – neutron – pulsars: individual: PSR J1012 + 5307.

1 INTRODUCTION

Binary millisecond radio pulsars (BMPs) consisting of a neutron star and a low-mass, possibly degenerate, companion are thought to represent a stage in the evolution of low-mass X-ray binaries (LMXBs), possibly producing isolated millisecond pulsars in some cases (see e.g. Bhattacharaya & van den Heuvel 1991 for a review). In this scenario, LMXB neutron stars accrete a fraction of a solar mass over the course of their lifetimes, with the concomitant increase in angular momentum decreasing their spin periods to tens of milliseconds or less. Once the envelope of the donor star is exhausted, mass transfer is terminated, and the neutron star appears as a radio pulsar. For the more luminous pulsars in the tighter binary systems, the evaporation of the low-mass companion by the high-energy emission from the neutron star may then ensue, leaving an isolated millisecond pulsar. Such a process may also explain the dearth of short-period LMXBs (van den Heuvel and van Paradijs 1988).

If all neutron stars are born with comparable masses, then one would expect those in LMXBs and their BMP descendants to be anomalously 'heavy' as a result of prolonged accretion over the lifetime of the system. Indeed, neutron star masses as high as $\sim$2–3 $\mathrm{M}_\odot$ are theoretically possible (e.g. see the discussion by van Paradijs & McClintock 1995). The neutron stars for which the most accurate mass estimates exist (those in neutron star–neutron star binaries) have masses $\sim 1.4 \pm 0.1$–0.2 $\mathrm{M}_\odot$. However, these are likely descendants of high-mass X-ray binaries, which are thought to have much shorter lifetimes than LMXBs, owing to the (initially) more massive nature of the secondary; hence they would have accumulated less material than their LMXB/BMP counterparts.

Accurate measurements of neutron star masses are difficult. For those BMPs that are likely LMXB descendants, only one such measurement exists (for PSR B1855 + 09) – yielding a neutron star mass of $\sim 1.50^{+0.26}_{-0.14}$ $\mathrm{M}_\odot$ (Kaspi, Taylor & Ryba 1994).

PSR J1012 + 5307, a 5.3 ms pulsar in a 14.5 h binary, was recently discovered by Nicastro et al. (1995). A $V = 19.6$ optical counterpart was soon identified, whose colour and magnitude are consistent with a low-mass ($M_2 \sim 0.02$ $\mathrm{M}_\odot$), low-temperature ($T_{\mathrm{eff}} \sim 9000$ K) degenerate companion (Lorimer et al. 1995). The relatively bright optical counterpart provides a unique opportunity to obtain detailed optical spectroscopy of the degenerate companion of a BMP: spectra of similar quality have only recently been obtained for two other BMPs by van Kerkwijk & Kulkarni (1995). Detailed spectroscopy allows us not only to measure the radial velocity of the white dwarf about its neutron star companion, but also to determine its mass with relative accuracy; mass estimates for the secondary stars in LMXBs are much more uncertain (e.g. van Paradijs & McClintock 1995). Combined with the orbital parameters of the pulsar, we can then solve for both the orbital inclination and neutron star mass. We describe our observations below.

2 OBSERVATIONS

PSR J1012 + 5307 was observed with the Multiple Mirror Telescope (MMT) on Mount Hopkins (Arizona) on the nights of 1996

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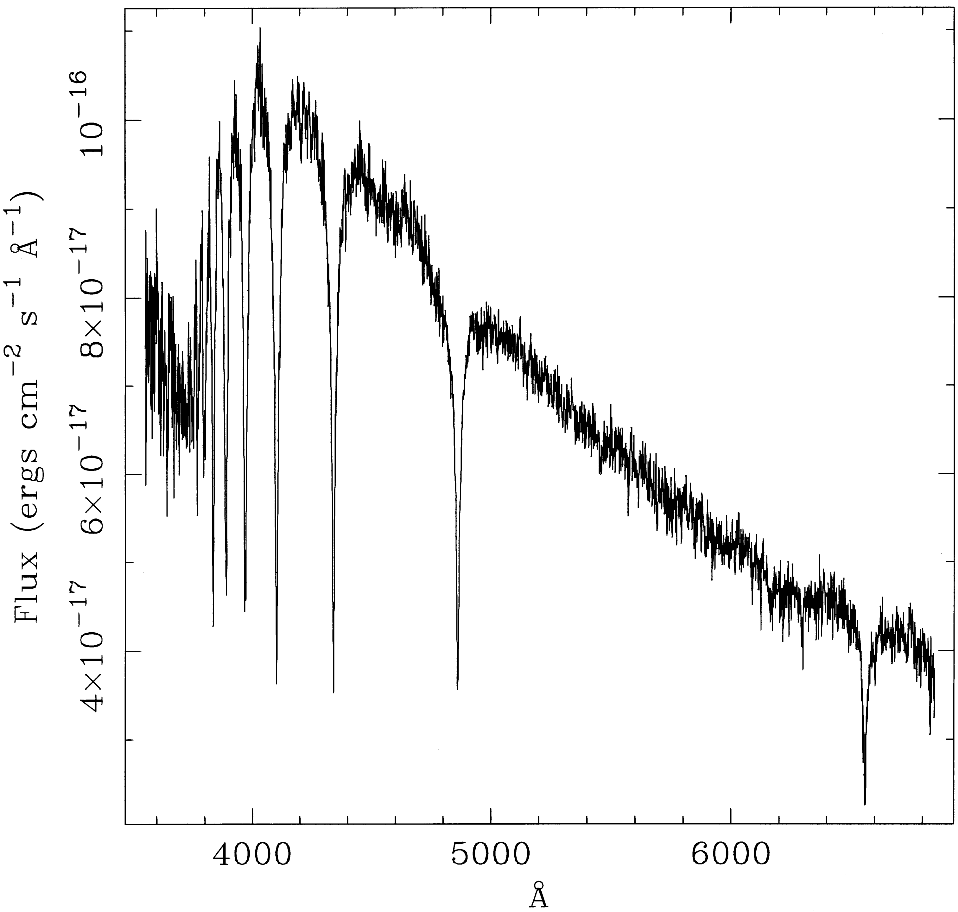

Figure 1. The summed spectrum of the white dwarf companion to PSR J1012 + 5307. The individual spectra have been Doppler-shifted, using the corrections calculated from Fig. 2.

May 8–11, using the 'blue channel' spectrograph. A 500 line mm^{-1} grating was used, giving a resolution of 3.6 Å (1.19 Å pixel^{-1} dispersion), covering a spectral range of $\sim$3600 Å. A series of 20 min exposures of the pulsar were obtained, each followed by an arc lamp measurement for accurate spectral calibration (although the spectrograph itself is extremely rigid, with a total shift of only $\sim$0.3 pixel per night). For three of our four nights the seeing was $\sim$1 arcsec or better, and hence we used a 1.0 arcsec slit. The seeing degenerated to $\sim$1.5 arcsec on the third night, and we used a correspondingly wider (1.5 arcsec) slit. In all cases the slit was kept at the parallactic angle.

The spectra were extracted using IRAF, and flux calibrated using the spectrophotometric standard Feige 34. The summed spectrum is shown in Fig. 1. The spectrum shows the Balmer lines Hα through to H11, as well as a clearly defined Balmer jump. The lines are broad, with a full width at half-maximum (FWHM) of $\sim$1200 km s^{-1} at Hβ, indicative of a degenerate, but relatively low-mass, companion.

Indeed, the width of these lines severely complicates the extraction of reliable radial velocity measurements. We proceeded as follows: First, each spectrum was 'flattened' by dividing it by the mean continuum; this was achieved by fitting it to a three-piece spline while ignoring the absorption lines. The data were then smoothed using a high-frequency blocking filter; the high-frequency cut-off we used had a wavenumber of $\sim$17, which corresponds to $\sim$2 pixel smoothing. Then a model was created for cross-correlation, using synthetic Balmer line profiles somewhat narrower than those of the object itself as a template. Narrower lines were chosen in an attempt to minimize the centroid measurement error of the cross-correlation peak (see below).

Each spectrum was then cross-correlated with this template model using the IRAF FXCOR package. We fitted from the Balmer jump to Hβ (Hα has too low a signal); our data do not have the signal-to-noise ratio necessary to fit each line separately. The velocity shift of each spectrum was finally calculated by fitting a Lorentzian to each FXCOR cross-correlation peak. We fitted seven to nine points around each peak; although the measured velocity depends on which points were chosen, this variation is only about a few kilometres per second.

As a check on the stability of this analysis, we also monitored the radial velocity of Feige 34 every night. While this star is not a radial velocity standard, it did yield a consistent velocity with a rms value of 4.2 km s^{-1} when the individual observations were cross-correlated with the synthetic Balmer spectrum. The arc lamps, sky lines and Feige 34 measurements are all stable to within these errors. The radial velocity curve of the pulsar was then folded on the radio ephemeris of Lorimer et al. (1995). Other authors (e.g. Filippenko, Matheson & Barth 1995) have found that FXCOR overestimates the radial velocity measurement error by a factor of $\sim$2; we found that dividing the FXCOR errors by 2 resulted in an acceptable reduced χ^2 of 1.2 (for a sine wave fit to the data). We excluded two data points that lay > 4σ from the best-fit sine wave. We plot this curve in Fig. 2: the semi-amplitude of the curve is 218 ± 10 km s^{-1}, with a γ velocity of 44 ± 8 km s^{-1}. These errors have been calculated for

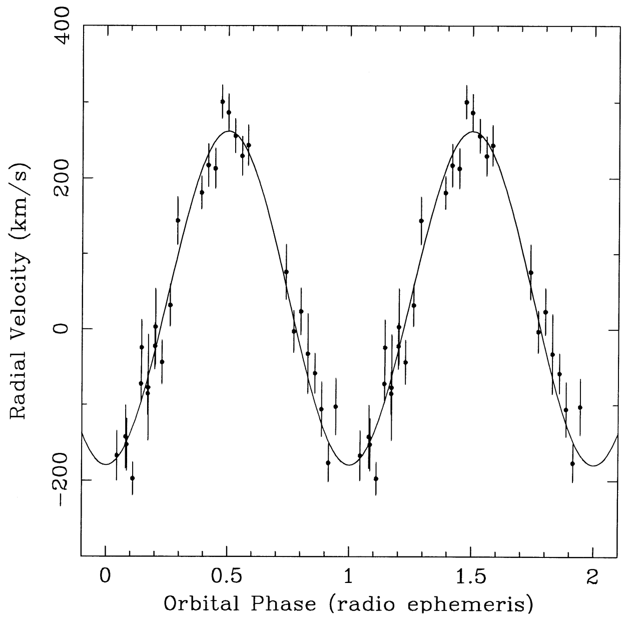

Figure 2. The radial velocity curve of the companion. The data have been folded on the radio ephemeris of Lorimer et al. (1995).

two parameters of interest (e.g. $\delta\chi^2 = 4.61$ per 90 per cent confidence level): all errors in this paper are quoted at the 1σ level. There is no evidence for any orbital eccentricity in the folded data, in agreement with the timing measurements of the pulsar.

3 DISCUSSION

Armed with the radial velocity semi-amplitude of the white dwarf secondary (of mass M_2), we can immediately combine this with the orbital parameters of the radio pulsar to derive a mass ratio q ($\equiv M_1/M_2$) = 10.5 ± 0.5. Here the uncertainty is dominated by the error in the amplitude of the radial velocity curve. To calculate the mass of the neutron star, we need first to estimate the mass of the white dwarf companion by fitting the spectra to models of low-mass white dwarf atmospheres.

3.1 The mass and temperatures of the white dwarf component

The spectra of the white dwarf were analysed with a grid of DA model atmospheres calculated with the Kiel LTE model codes – see Koester, Schulz & Weidemann (1979) and Finley, Koester & Basri (in preparation) for a description. The usual grid for normal white dwarfs extends down to the surface gravity of $\log g = 7.0$; for this object we calculated new models down to $\log g = 6.0$ with a step of 0.1 in $\log g$ and 250 K in T_{eff}.

The comparison between the observed spectra and theoretical models was achieved using a χ^2 fitting techniques. In this procedure we forced agreement in the continuum between Balmer lines, thus using essentially only the normalized line profiles of Hα to H9 in the fit. Fig. 3 shows the comparison with the best-fitting model for the summed spectrum. It is very difficult to assess the magnitude of the 1σ fitting errors, but an indication may be obtained from varying the parameters of the fitting routine (within reasonable limits). All solutions we obtained in such an exercise were constrained within $T_{\mathrm{eff}} = 8670 \pm 300$ K, $\log g = 6.34 \pm 0.20$, which we therefore adopt as our final result.

While for normal DA white dwarfs it is fairly well established that the composition is almost pure hydrogen, this need not

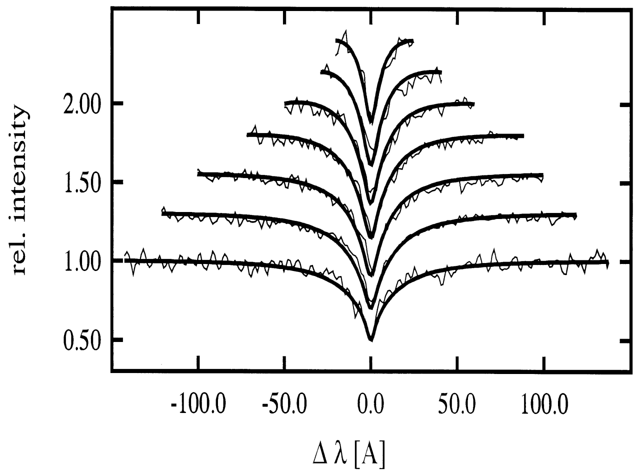

Figure 3. Comparison between the best-fit atmosphere and the spectrum of Fig. 1. The model parameters are $T_{\mathrm{eff}} = 8670$ K, and $\log g = 6.34$. Lines are Hα to H9 from bottom to top; higher lines are shifted upwards for clarity.

necessarily be the case for this object. We repeated the model fitting procedure with a grid of models using a H/He number ratio of 10, i.e. the solar ratio. The best fit with these models is obtained for $T_{\mathrm{eff}} = 8660$ K, $\log g = 6.23$. This result is within our adopted error range.

In order to determine a white dwarf mass from the surfaace gravity, we need a mass–radius relation for very low-mass white dwarfs. The widely used evolutionary calculations of Wood (e.g. Wood 1995) end at 0.4 $M_{\odot}$, corresponding to a $\log g$ of about 7.6 at this T_{eff}. Calculations for very low-mass helium white dwarfs have been reported for a few selected masses in the context of close binary evolution (Webbink 1975; Iben and Tutukov 1986). We are not aware of any systematic study in the literature of the mass–radius relation at $T_{\mathrm{eff}} \sim 8500$ K for white dwarfs with small masses, with the exception of the very recent paper by Alberts et al. (1996), which reaches only down to $\log g = 6.5$.

We have therefore performed our own study of finite-temperature white dwarf models, using programs originally developed for the calculation of finite-temperature mass–radius relations and the construction of equilibrium models in white dwarf pulsation studies (Koester 1978; Dziembowski and Koester 1981). With this code we have calculated low-mass models for helium white dwarfs, with a fractional H layer of 10^{-4} of the total mass, for effective temperatures of 8300, 8600 and 8900 K.

Our calculations are not evolutionary calculations; we simply solve the equations of stellar structure, circumventing the problem that white dwarfs are not in thermal equilibrium by assuming that $L(r) \propto m(r)$, i.e. that the energy generation per unit mass is constant. That this assumption leads to reasonable results is confirmed by the excellent agreement with the calculations of Alberts et al. (1996) in the region of overlap (see also Rappaport et al. 1995).

We could extend our calculations down to 0.15 $M_{\odot}$; at lower masses numerical problems prevented convergence of the models. We believe, however, that this is not only a numerical problem, but that white dwarfs with significantly lower masses cannot exist at these effective temperatures. Already in the 0.15 $M_{\odot}$ model the degeneracy at the centre is quite low. The 0.10 $M_{\odot}$ model of Webbink (1975) never reaches an effective temperature as high as 8600 K during its evolution, confirming our results.

The results of this calculation are shown in Fig. 4, with the possible range given by the atmospheric parameters shaded in grey.

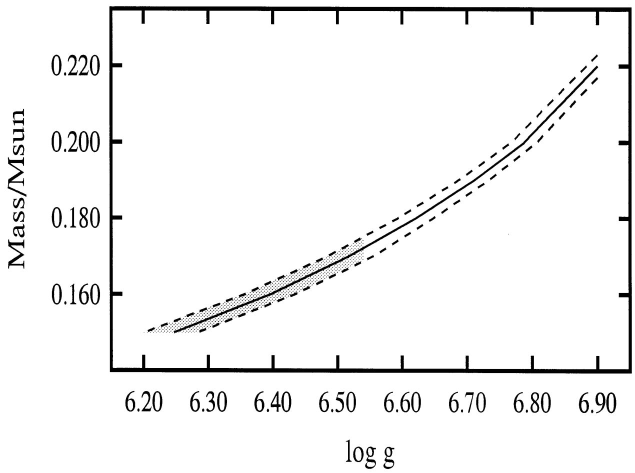

Figure 4. Mass–log *g* relation for very low-mass helium white dwarfs with outer hydrogen layers. The shaded area indicates the parameter range allowed by the optical observations.

The mass we obtain from the best solution for the atmospheric parameters (8670/6.34) is 0.156 ± 0.020 M$_\odot$, where the lower limit is obtained only by an extrapolation of our mass–radius relation.

3.2 The distance to the pulsar

Our model shows that the absolute magnitude (M_v) of a white dwarf of this mass is ~9.97. By comparison, scaling the absolute magnitudes of ~A2 main-sequence stars (e.g. Popper 1980) to the radius of the white dwarf in PSR J1012 + 5307 yields $M_v \sim 9.8$. The corresponding distance is 840 ± 90 pc (where we use $M_v = 9.97$, and assume an error of 0.2 in the absolute magnitude calibration). This distance is considerably more than the ~520 pc inferred from the dispersion measure (Nicastro et al. 1995): however, it may simply point to an unusually underabundant free-electron distribution in this location of the Galaxy (e.g. Halpern 1996).

3.3 The mass of the neutron star

Combining the mass of the white dwarf with the mass ratio yields a neutron star mass of 1.64 ± 0.22 M$_\odot$, where the error is dominated by the uncertainty in the white dwarf mass discussed above. The orbital inclination is then 52 ± 4 deg. Although our mass estimate is nominally somewhat higher than the canonical value of 1.4 M$_\odot$, we consider it consistent within the errors of our measurement.

Assuming an initial secondary mass ~1 M$_\odot$, ~0.8 M$_\odot$ must have been lost from the donor star during the binary evolution. Hence, our results suggest that only a fraction (< 50 per cent) of this was successfully accreted onto the neutron star (for an initial mass of ~1.4 M$_\odot$). Such mass loss, if confirmed, may have been caused by the strong X-ray irradiation of the secondary during the LMXB phase, and/or efficient mass loss via a strong wind from the accretion disc. We note that optical and *HST* observations of X-ray binaries – e.g. AC211 in M15 (Ilovaisky 1989), Her X-1 (Anderson et al. 1994) and 4U1822 − 371 (Callanan, in preparation) – are beginning to show evidence for P-Cygni profiles or extended emission-line regions that may be the hallmark of such a wind, although it remains to be seen if these winds can maintain such large mass-loss rates.

If the progenitor of PSR J1012 + 5307 was a persistently bright LMXB with $L_x \sim 10^{37-38}$ erg s^{-1}, then $\dot{m} \times \tau \lesssim 0.2 \pm 0.2$ M$_\odot$ (where $\dot{m}$ is the mean accretion rate in M$_\odot$ yr^{-1}, and τ the lifetime of the LMXB) and $\tau \lesssim 3 \times 10^{7-8}$ yr (again for an initial neutron star mass of 1.4 M$_\odot$). This lifetime is somewhat shorter than that usually assumed for LMXBs: indeed, the lower estimate may be sufficient to reconcile the well-known discrepancy between LMXB and BMP birth rates (e.g. Bhattacharya 1995). However, if the progenitor LMXB were an X-ray transient (e.g. a system similar to Cen X-4 or Aql X-1), then a much lower accretion rate and correspondingly longer lifetime are also possible. It is clear that neutron star mass measurements of other LMXB and their BMP descendants are required.

4 CONCLUSIONS

We have measured the radial velocity variation of the white dwarf secondary in the binary system containing the millisecond pulsar PSR J1012 + 5307. Combined with the orbital parameters of the neutron star inferred from radio observations, we infer a mass ratio $q\ (\equiv M_1/M_2) = 10.5 \pm 0.5$. Our optical spectroscopy has also allowed us to determine the mass of the white dwarf companion by fitting the spectrum to a grid of DA model atmospheres: we estimate $M_2 = 0.156 \pm 0.02$ M$_\odot$, and hence the mass of the neutron star is 1.64 ± 0.22 M$_\odot$, where the error is dominated by that of M_2. For an initial secondary mass of 1 M$_\odot$, our neutron star mass estimate suggests that the mass transfer during the LMXB phase may have been non-conservative. If the progenitor was a persistently bright LMXB, then the epoch of mass transfer is likely to have been $\lesssim 3 \times 10^{7-8}$ yr.

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NOTE ADDED IN PROOF

While this work was in progress, we became aware of the observations of the same pulsar by van Kerkwijk, Bergeron & Kulkarni (1996). Although our neutron star mass estimate is somewhat smaller than theirs, it none the less falls within their 95 per cent confidence limits (1.5 < M$_\odot$ < 3.2). However, the γ velocities do appear to be inconsistent; it is possible that systematic effects may be playing a larger role in the radial velocity analysis than previously thought.

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