On the mass of the neutron star in Cyg X-2

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ABSTRACT

We present new high-resolution spectroscopy of the low-mass X-ray binary Cyg X-2, which enables us to refine the orbital solution and rotational broadening of the donor star. In contrast with Elebert et al., we find a good agreement with results reported in Casares et al. We measure $P = 9.84450 \pm 0.00019$ d, $K_2 = 86.5 \pm 1.2$ km s$^{-1}$ and $V \sin i = 33.7 \pm 0.9$ km s$^{-1}$. These values imply $q = M_2/M_1 = 0.34 \pm 0.02$ and $M_1 = 1.71 \pm 0.21$ M$_{\odot}$ (for $i = 62.5 \pm 4$°). Therefore, the neutron star in Cyg X-2 can be more massive than canonical. We also find no evidence for irradiation effects in our radial velocity curve which could explain the discrepancy between Elebert et al.’s and our $K_2$ values.

Key words: accretion, accretion discs – binaries: close – stars: individual: Cygnus X-2 – X-rays: binaries.

1 INTRODUCTION

Dynamical studies in low-mass X-ray binaries (LMXBs) offer a promising route to the test of equation of state of nuclear matter. Soft equations of state are not stable above 1.6 M$_{\odot}$ (e.g. Brown & Bethe 1994), and hence finding a neutron star more massive than this limit would be a major advance in our knowledge of nuclear matter physics. LMXBs and, in particular, accreting millisecond pulsars (AMPs) are expected to harbour the most massive neutron stars because of the sustained accretion of matter during their long lives (van den Heuvel & Bitzaraki 1995). Unfortunately, dynamical studies are hampered by (i) the overwhelming accretion luminosity in persistent LMXBs (which swamps the donor star’s spectrum) and (ii) the extreme faintness of the companion star in transient AMPs during quiescence (D’Avanzo et al. 2009).

A promising route to overcome these limitations was proposed by Steeghs & Casares (2002). X-ray irradiated donor stars can be betrayed by the detection of high excitation fluorescence N iii and C iii lines within the Bowen blend at 4634–50 Å. The Doppler shift of these narrow lines traces the orbit of the donor star and, therefore, can yield dynamical constraints in persistent LMXBs and transient AMPs during an outburst. As a result of this strategy, some good candidates for massive neutron stars have been found, namely X1822-371 (Muñoz-Darias, Casares & Martínez-Pais 2005) and Aql X-1 (Cornelisse et al. 2007).

In a few long period ($P > 1$ d) systems, the donor is an evolved star which can be spectroscopically detected over the irradiated accretion disc. Cyg X-2 represents one of these exceptional cases.

Its first orbital solution was presented by Cowley, Crampton & Hutchings (1979), who show that the donor star is an A5-F2 III orbiting the neutron star in 9.843 d with a projected velocity of $K_2 = 87 \pm 3$ km s$^{-1}$. Almost 20 years later, this was refined by Casares, Charles & Kuulkers (1998) (hereafter C98) who found an A9 donor with orbital parameters $P_{\text{orb}} = 9.8444 \pm 0.0003$ d and $K_2 = 88.0 \pm 1.4$ km s$^{-1}$. This work also reports the first determination of the rotational broadening of the donor’s absorption features ($V \sin i = 34.2 \pm 2.5$ km s$^{-1}$) which, in turn, implies a binary mass ratio $q = M_2/M_1 = 0.34 \pm 0.04$. This value is remarkable as it implies a peculiar donor star, very undermassive for its spectral type and the probable outcome of an intermediate-mass binary (King & Ritter 1999; Podsiaidowski & Rappaport 2000; Kolb et al. 2000). But the implications for the compact object’s mass are also remarkable. The orbital solution, combined with inclination constraints $i = 62.5 \pm 4$° derived through ellipsoidal fits to $UBV$ light curves, gives a neutron star mass of 1.78 $\pm 0.23$ M$_{\odot}$ (Orosz & Kuulkers 1999) and, hence, a good candidate for a massive neutron star. This result has been recently challenged by Elebert et al. (2009) (hereafter E09) who measure $K_2 = 79 \pm 3$ km s$^{-1}$ and hence $M_1 = 1.5 \pm 0.3$ M$_{\odot}$.

Here, we present new high-resolution spectroscopic observations of Cyg X-2 with the main aim of refining the rotational broadening of the donor star and update the orbital parameters. In contrast with E09, we find a good agreement with previous results reported in C98 which give support to the presence of a massive neutron star in Cyg X-2.

2 OBSERVATION AND DATA REDUCTION

Cyg X-2 was observed on the nights of 1999 July 25–26 using the Utrecht Echelle Spectrograph (UES) attached to the 4.2-m William Herschel Telescope (WHT) at the Observatorio del Roque de Los
Muchachos. Ten 1800–3600 s spectra were obtained with the E31 echelle grating and 2 K×2 K SITE1 detector, covering the spectral range of λλλ5300–9000 Å. We selected a 1 arcsec slit and a factor of 2 binning in the spectral direction, resulting in 10 km s⁻¹ resolution. ThAr arc images were observed each night for the purpose of wavelength calibration. The final wavelength calibration was verified using the OI skylines at λ5577.34 and λ6300.304, and variable velocity offsets were found between 0.2 and 5 km s⁻¹. These were corrected from every individual spectrum.

11 additional spectra were obtained on the nights of 1999 July 31 and 2000 July 9 with the Intermediate dispersion Spectrograph and Imaging System (ISIS) on the WHT. Here, we employed the 1200B grating on the blue arm and different central wavelengths resulting in wavelength coverages within λλλ3550–6665. A 1 arcsec slit was selected yielding spectral resolutions in the range 34–54 km s⁻¹. Frequent comparison CuAr+CuNe arc lamp images were taken every night for wavelength calibration. This was tested against sky lines, and it was found to be accurate to within 4 km s⁻¹. These small offsets were nevertheless corrected from the individual spectra. The ISIS red arm was always centred redwards of 7600 Å but is not used in this paper due to its lower spectral resolution and the paucity of absorption lines, which result in larger errors in the cross-correlation analysis. The red arm spectra were mainly taken for the sake of abundance analysis, and will be reported elsewhere (González Hernández I. I. et al., in preparation). A log of the observations is presented in Table 1.

For the purpose of radial velocity analysis, we observed the stellar template HR 114 (A7 III) using all different instrumental configurations. This star has an intrinsic $V \sin i$ of 21 km s⁻¹, i.e. comparable to the rotational broadening of the donor star in Cyg X-2 (C98). Therefore, to refine our previous rotational broadening we decided also to observe the F3 V star HR 6189 with UES, which has a reported upper limit $V \sin i < 15$ km s⁻¹.

All the images were processed following standard debiasing and flat-fielding, and the spectra subsequently extracted using conventional optimal extraction techniques in order to optimize the signal-to-noise ratio of the output (Horne 1986).

### 3 REVISITING THE ROTATIONAL BROADENING

In C98, we measured the rotational broadening of the donor star’s features in Cyg X-2 using 25 km s⁻¹ resolution spectra and found $V \sin i = 34.2 \pm 2.5$ km s⁻¹. Here, we revisit this determination using the 10 km s⁻¹ UES spectra. We broadened the template star HR 6189 from 5 to 50 km s⁻¹ in steps of 1 km s⁻¹, using a Gray profile (Gray 1992) and a limb-darkening coefficient $\epsilon = 0.5$ appropriate for our spectral type and wavelength range. The broadened templates were rectified to the continuum (using a low-order spline fit) and multiplied by factors $f < 1$, to account for their fractional contribution to the total light. These were subsequently subtracted from the Doppler-corrected average of Cyg X-2, obtained using the orbital solution given in Section 4. The Cyg X-2 average was also rectified through fitting a low-order spline to the continuum, after masking out the main emission and atmospheric/IS absorption lines. The optimal broadening, based on a $\chi^2$ test on the residuals, is found for $34.6 \pm 0.1$ km s⁻¹. A potential source of systematics is the assumption of continuum limb-darkening coefficient in the computation of the rotational profile. Absorption lines in late-type stars are expected to have smaller core limb-darkening coefficients than the continuum (Collins & Truax 1995) and, therefore, assuming the continuum limb-darkening coefficient could bias the result. This was tested by repeating the same analysis using zero limb darkening as a conservative lower limit and obtaining $V \sin i = 32.8 \pm 0.1$ km s⁻¹. Therefore, we decide to adopt the mean of the two limb-darkening values as a safe estimate of the true rotational broadening in Cyg X-2, i.e. $V \sin i = 33.7 \pm 0.9$ km s⁻¹ (see Fig. 1). This is in excellent agreement with our determination in C98.

### 4 UPDATED ORBITAL SOLUTION AND MASSES

We rectified the 21 individual spectra by subtracting a low-order spline fit to the continuum, after masking out the main emission and absorption features. The UES spectra were subsequently rebinned into a uniform velocity scale of 5 km s⁻¹ pixel⁻¹ and the ISIS spectra into 27 km s⁻¹ pixel⁻¹. Radial velocities were extracted through cross-correlation of every individual spectrum of Cyg X-2 with its corresponding A7 III template HR 114, observed with
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identical instrumental setup. The template spectra were previously broadened to 33 km s\(^{-1}\) to match the width of the donor photospheric lines (see the previous section). Cross-correlation was performed in the spectral regions free from emission and telluric absorption features. For consistency, new radial velocities were extracted from the old data base (C98) using a contemporaneous observation of the template HR 114, obtained for the purpose of spectral classification. Radial velocities were extracted following the method of Tony & Davis (1979), where parabolic fits were performed to the peak of the cross-correlation functions, and the uncertainties are purely statistical. The final error bars were multiplied by a factor of 2, so that the minimum reduced \(\chi^2\) of a sine-wave-fit model is 1.0. This yields the following parameters:

\[
\begin{align*}
\gamma &= -209.9 \pm 1.4 \text{ km s}^{-1} \\
P &= 9.84450 \pm 0.00019 \text{ d} \\
T_0 &= 2451387.148 \pm 0.018 \\
K_2 &= 86.5 \pm 1.2 \text{ km s}^{-1},
\end{align*}
\]

where \(T_0\) corresponds to the inferior conjunction of the donor star. All quoted errors are 68 per cent confidence. The systemic velocity \(\gamma\) has been corrected from the radial velocity of HR 114, that we take as \(-10.2 \pm 0.9 \text{ km s}^{-1}\) (Wilson 1953). Fig. 2 displays the radial velocity points folded on the orbital period together with the best sine-wave-fit solution. New radial velocities are marked with open circles whereas solid circles indicate velocities from the old 1993–1997 ISIS data base. The dashed line depicts the orbital solution of E09.

\[
\begin{align*}
\sigma_3 &\text{ for 60 degrees of freedom, and hence it is far less significant than our } K_2 \text{ value (Lampton, Margon \\
& Bowyer 1976). E09 have suggested that the difference between the two } K_2 \text{ values could be caused by different levels of X-ray irradiation between the two observing epochs. The detection of He } \pi \lambda 4686 \text{ emission from the companion by E09 certainly indicates that the star is irradiated. However, it remains to be seen whether irradiation is sufficient, not only to pump chromospheric He } \pi \text{ emission, but also to modify the surface distribution of the photospheric absorption lines. In principle, irradiation can quench absorption lines from the inner hemisphere of the donor star, leading to an increase in the observed } K_2 \text{ (Wade & Horne 1988). It might be possible that, by a chance coincidence, the E09 data base was obtained during an episode of lower X-ray activity than our data, and we have looked for this using } RXTE/\text{All Sky Monitor (ASM) data. Contemporaneous X-ray observations are available for the second half of the C98 campaign since 1996, when } RXTE \text{ was launched, our new data from 1999–2000 and the entire E09 data base, but comparable levels of X-ray activity are found with the X-ray flux } F_X \text{ oscillating between 35 and 50 ASM counts s}^{-1}. \text{ Only one velocity point in C98, obtained on the night of 1996 August 5, was taken during a dip in the X-ray light curve of } \sim 18 \text{ counts s}^{-1}. \text{ Interestingly, its orbital phase is } \phi = 0.63, \text{ almost identical to that of another point obtained on 1997 August 3 (} \phi = 0.67\text{), when } F_X \geq 50 \text{ counts s}^{-1} \text{ i.e. almost a factor of 3 higher. Despite the difference in X-ray flux, both velocities are consistent with our best orbital solution within } 1\sigma. \text{ Moreover, one should note that phase 0.65 is close to an orbital quadrature, when velocity distortions from a circular orbit should be largest (e.g. Davey & Smith 1992). This strongly suggests that the effects of X-ray irradiation in the radial velocity curve are unimportant.}
\end{align*}
\]

As a matter of fact, irradiation will distort the radial velocity curve from a simple sine wave, introducing a fictitious eccentricity, which should be measurable. Therefore, we have also attempted to fit elliptical orbits to our data base, following Friend et al. (1990). Our best fit yields null eccentricity (\(e = 0.004 \pm 0.019\)) and a larger reduced \(\chi^2\) than a simple circular solution, another indication that irradiation is negligible at this level. Furthermore, Orosz & Kuulkers (1999) find no evidence for excess light at phase 0.5 in their optical light curves nor did C98 observe any significant change of spectral type with orbital phase. These two results also suggest that X-ray irradiation is not enough to explain the discrepant \(K_2\) values. The lack of irradiation signatures is probably due to the fact that the donor star is hot and the orbital separation large. The X-ray flux received by every surface element on the companion star is too small to produce any disturbance in the radial velocity curve or light curve, despite the near Eddington X-ray luminosity of Cyg X-2.

Looking at the radial velocity curve of E09 (shown in their fig. 4) we note a large scatter in the velocity points near the phase 0.25 quadrature. Two data points seem to lie systematically lower than the rest by \sim 20 \text{ km s}^{-1}, and this is certainly dragging the \(K_2\) velocity to lower values. The authors admit that only one arc spectrum was obtained for most of the nights. Although sky lines were used to correct for instrumental offsets, the fact that the strongest sky line O \ii \lambda 5577 lies at the edge of their spectral range may introduce some systematics in the offset correction. Therefore, we believe that the value reported by E09 might be affected by problems with the wavelength calibration, which is a critical issue given their low spectral resolution of \sim 160 \text{ km s}^{-1}. In any case, new
high-resolution observations obtained at the two orbital quadratures are clearly required to further constrain $K_2$ and confirm our result.

Since the donor star is filling its Roche lobe and synchronized, we can combine our updated $K_2$ and $V \sin i$ values to constrain the binary mass ratio through

$$V \sin i = K_2 (1 + q) \frac{0.49 \, q^{2/3}}{0.6 \, q^{2/3} + \ln (1 + q^{1/3})}$$

(Horne, Wade & Szkody 1986), which leads to $q = 0.34 \pm 0.02$. The revised mass function is thus $f(M) = M_1 \sin^3 i / (1 + q^2) = PK_2^2 / 2 \pi G = 0.66 \pm 0.03$ and hence $M_1 \sin^3 i = 1.19 \pm 0.06 \, M_\odot$. Assuming $i = 62.5 \pm 4^\circ$ (Orosz & Kuulkers 1999), we find $M_1 = 1.71 \pm 0.21 \, M_\odot$. The error budget is clearly dominated by the uncertainty in the inclination angle, and thus ellipsoidal model fits to new light curves are urgently needed to better constrain the stellar masses.

5 SUMMARY

We have revisited the determination of the system parameters in Cyg X-2 with 21 new high-resolution spectra obtained during 1999 and 2000. The new solution does not support the conclusions of E09 who claim for a significantly lower value for the radial velocity semi-amplitude of the donor star. Instead, our results confirm previous determinations reported in C98. The discrepancy cannot be explained by X-ray irradiation because the sinusoidal shape of the radial velocity curve is not disturbed. In particular, we find (i) no evidence for orbital eccentricity and (ii) no significant deviations between two velocity points at phase $\sim 0.65$, when X-ray flux varies by a factor of $\sim 3$. Our refined orbital parameters are $P = 9.84450 \pm 0.00019 \, d$, $K_2 = 86.5 \pm 1.2 \, \text{km s}^{-1}$ and $V \sin i = 33.7 \pm 0.9 \, \text{km s}^{-1}$, which lead to $q = 0.34 \pm 0.02$, $M_1 \sin^3 i = 1.19 \pm 0.06 \, M_\odot$. Assuming $i = 62.5 \pm 4^\circ$ from Orosz & Kuulkers (1999) leads to $M_1 = 1.71 \pm 0.21 \, M_\odot$, and therefore the possibility that Cyg X-2 harbours a neutron star more massive than canonical.

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