THE MASS OF THE NEUTRON STAR IN CYGNUS X-2 (V1341 CYGNI)

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ABSTRACT

Cyg X-2 is one of the brightest and longest known X-ray sources. We present high-resolution optical spectroscopy of Cyg X-2 obtained over 4 yr, which gives an improved mass function of \( 0.69 \pm 0.03 \, M_\odot \) (1 o). In addition, we resolve the rotationally broadened absorption features of the secondary star for the first time, deriving a rotation speed of \( v \sin i = 34.2 \pm 2.5 \, \text{km s}^{-1} \) (1 o), which leads to a mass ratio of \( q = M_2/M_1 = 0.34 \pm 0.04 \) (1 o, assuming a tidally locked and Roche lobe-filling secondary). Hence, with the lack of X-ray eclipses (i.e., \( i \approx 73^\circ \)) we can set firm 95% confidence lower limits to the neutron star mass of \( M_1 > 1.27 \, M_\odot \) and to the companion star mass of \( M_2 > 0.39 \, M_\odot \). However, by additionally requiring that the companion must exceed 0.75 \( M_\odot \) (as required theoretically to produce a steady low-mass X-ray binary), then \( M_1 > 1.88 \, M_\odot \) and \( i < 61^\circ \) (95% confidence lower and upper limit, respectively), thereby making Cyg X-2 the highest mass neutron star measured to date. If confirmed, this would set significant constraints on the equation of state of nuclear matter.

Subject headings: accretion, accretion disks — binaries: close — stars: individual (Cyg X-2, V1341 Cygni) — X-rays: stars

1. INTRODUCTION

The distribution of neutron star masses provide fundamental constraints on the equation of state of condensed matter. Very precise determinations (e.g., Thorsett et al. 1993; Nice, Sayer, & Taylor 1996) are available from time delays in millisecond radio pulsars and are all consistent with 1.38 \( \pm 0.07 \, M_\odot \). Dynamical masses can also be obtained for accreting neutron stars in X-ray binaries. In particular, high-mass X-ray binaries (HMXBs) would appear to be ideal candidates because the orbit of the two components are measurable through spectroscopic Doppler shifts and X-ray pulses. This, combined with a determination of the inclination angle through X-ray eclipses (when favorable), leads to a full solution for the system parameters. Following this strategy, six neutron star masses have been obtained, and they all lie in the range 1.0–1.9 \( M_\odot \) (see van Kerkwijk, van Paradijs, & Zuiderwijk 1995, and references therein). However, the uncertainties involved in these determinations can be quite large owing to non-Keplerian perturbations in the radial velocity curves. These are very difficult to assess and are caused by a variety of effects such as stellar wind contamination, tidal distortion of the companion and X-ray heating. On the other hand, mass determinations in low-mass X-ray binaries (LMXBs) are very difficult to obtain both because their neutron stars do not (usually) pulse and the optical companions are normally overwhelmed by X-ray reprocessed radiation (van Paradijs & McClintock 1995). Only in a few exceptional cases can the companion be detected (when it is evolved or during X-ray off-states), and thus it becomes feasible to extract dynamical information and set constraints on the system parameters.

Cyg X-2 is one of the few LMXBs in which the spectrum of the nondegenerate star is visible, contributing about 50% of the total visual flux. Estimates of the absolute magnitude of the donor and analysis of interstellar reddening (McClintock et al. 1984) imply a distance of ~8 kpc and hence an X-ray luminosity of \( L_X \sim 10^{38} \, \text{ergs s}^{-1} \). This large luminosity is consistent with near-Eddington accretion rates onto a neutron star as typically observed in LMXBs (e.g., Hasinger et al. 1990); the neutron star’s presence in Cyg X-2 is also indicated by the observation of X-ray bursts (e.g., Kuulkers, van der Klis, & van Paradijs 1995). The X-ray intensity and energy distribution are highly variable on different timescales, tracing out a “Z” shaped track in the so-called X-ray color-color diagram with three distinct spectral states (Kuulkers, van der Klis, & Vaughan 1996, and references therein). Hence, it is classified as a Z source (Hasinger & van der Klis 1989), the variations of which are believed to be triggered by mass transfer rate changes. Multiwavelength observations indicate that the strength of the UV continuum and the high-excitation lines are correlated with the states of the “Z” diagram (Vrtilek et al. 1990; van Paradijs et al. 1990). Spectral type variations (in the range A5–F2) with orbital phase have been reported, with the earliest spectral type occurring when viewing the X-ray irradiated hemisphere of the companion (Cowley, Crampton, & Hutchings 1979).

From 1993 onward we have collected high-resolution spectroscopy of Cyg X-2 with the aim of improving the system parameters and to resolve the rotation speed of the companion, thereby significantly refining the mass determination of the two components. In addition, we have searched for the presence of Li in the atmosphere of the companion star (see, e.g., Martín et al. 1994), the results and implications of which will be presented elsewhere (Martín et al. 1998, in preparation).

2. OBSERVATIONS

We obtained 40 red spectra (\( \lambda \lambda 6340–6800, 0.40 \, \text{Å pixel}^{-1} \) dispersion) of Cyg X-2 at the Observatorio del Roque de los Muchachos using the 4.2 m William Herschel Telescope (WHT), equipped with the ISIS triple spectrograph (Clegg et al. 1992), on the nights of 1993 December 16–19, 1994 October 23–24, 1994 December 25, 1996 August 5, 1996 December 3, and 1997 August 1–7. A 0′′8–1′′3 slit was used, depending on seeing conditions, giving spectral resolutions of 25–37 km s\(^{-1}\). Cu-Ne arc spectra were obtained after every 1800 s exposure of the target. For the sake of the spectral classification and rotational broadening analyses we also observed a grid of 34...
template stars using exactly the same spectral configuration (with the narrowest 0.8 slit) as for Cyg X-2. These stars cover a range of spectral types from A0 to F8 in luminosity classes III, IV, and V.

3. RESULTS

Individual radial velocities were extracted through cross-correlation of the red spectra with the template star HR 2489 (A9 III), after masking out the broad Hα and He i λ6678 emission lines. A subsequent sine wave fitted to the velocity points (Fig. 1) gave the following parameters (after renormalizing the minimum reduced χ² to 1): P = 9.8444 ± 0.0003 days; γ = −209.6 ± 0.8 km s⁻¹; K_c = 88.0 ± 1.4 km s⁻¹; T_c (HJD) = 2449339.50 ± 0.03, where T_c corresponds to the standard zero phase definition, i.e., inferior conjunction of the secondary star. These and all subsequent errors quoted are ± 1 σ. In order to explore any nonsymmetric effects in the radial velocity curve, e.g., artificial eccentricity induced by heating of the inner face of the companion (e.g., Davey & Smith 1992), we allowed the eccentricity e to be a free parameter in the fit. The presence of the eccentricity is only significant at the ∼75% confidence level; in this case we get e = 0.024 ± 0.015. Therefore, we conclude that a circular orbit represents the best description of the data points, and thus we assume that our measured K_c corresponds to the true velocity semiamplitude of the companion star. Our parameters are entirely consistent and substantially more accurate than those derived by Cowley et al. (1979) and Crampion & Cowley (1980).

Combining K_c and P in the expression for the mass function gives

\[ \frac{M_x \sin^3 i}{(1 + q)^2} = 0.69 \pm 0.03 \, M_\odot, \]  

where q = M_c/M_x is the system mass ratio.

Using the above above in the case of Cyg X-2, in the rest frame of the secondary. A spectral type classification of A9 ± 2 for the companion was then derived through two different techniques: optimal subtraction of spectral type standards in the regions λλ6380–6520, λλ6620–6665, λλ6700–6760 (further details to be found in Casares et al. 1997) and direct comparison of the Fe i line ratio λ6463/λ6457. The former method was also applied to Doppler sums at the two conjunction phases (−0.05–0.05 and 0.45–0.55), but no spectral type variation could be found (Fig. 2). Our result is in contradiction with Cowley et al. (1979), who claim orbital variations of the companion’s spectral type (due to X-ray heating) in the range A5–F2. However, we note that their result is based on the ratio Ca ii K to H, which is not a good diagnostic because the Balmer series (and perhaps also Ca ii K) are clearly filled in by variable emission cores. Indeed, it has been noted (Kristian, Sandage, & Westphal 1967; Cowley et al. 1979) that the Balmer lines in Cyg X-2 appear abnormally broad, which is expected if the absorption cores are filled in with emission. Therefore, we give more weight to the metal line ratios, which do not support spectral variations larger than two subtypes between the two conjunctions. We note that we actually detect an enhancement of the He i λλ6678 absorption at phase 0.5, together with an overall weakening of the metallic absorptions, produced by a ~60% increase in the continuum. These are indications of heating effects, although spectral type variations are not significant since the relative depth of the metallic lines is maintained throughout the orbit. We also note that the absence of spectral type variations is not due to changes in the overall average X-ray luminosity over the last ~20 yr. In fact, recent Rossi X-Ray Timing Explorer (RXTE) All-Sky Monitor measurements (Wijnands, Kuulkers, & Smale 1996) indicate the overall X-ray luminosity to be comparable to that measured during the observations of Cowley et al. (1979).

In order to measure the rotational velocity of the companion star (v sin i) only the highest resolution spectra (with a 0.8 slit) were employed. These correspond to the nights of 1996 De-
December 3 and 1997 August 1–7. The technique consists of performing a $\chi^2$ test on the residuals after subtracting different broadened versions of our templates from the Doppler-corrected sum of Cyg X-2. The template spectra were broadened through convolution with the rotational profile of Gray (1976, p. 398), which assumes a linearized limb darkening coefficient $(i \leq 73^\circ)$. The vertical dashed line indicates the maximum possible mass for the neutron star (3.2 $M_\odot$; e.g., Rhoades & Ruffini 1974). The horizontal dashed line indicates the mass of a main-sequence star (1.7 $M_\odot$; Allen 1973) of the same spectral type as observed for the companion in Cyg X-2 (A9).

$\nu \sin i = K_c \left(1 + q \right) \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln \left(1 + q^{1/3}\right)}$.  \hspace{1cm} (2)

Substituting our values of $\nu \sin i$ and $K_c$ in equation (2) we find $q = 0.34 \pm 0.04$, which, combined with equation (1) gives $M_2 \sin i = 1.25 \pm 0.09 M_\odot$. On the other hand, the absence of X-ray eclipses provides a severe upper limit to the inclination of $i \approx 73^\circ$. This provides the following 95% confidence lower limits to the masses of the components in Cyg X-2: $M_2 > 1.77 M_\odot$ and $M_1 > 0.39 M_\odot$. Results are plotted in Figure 4.

4. DISCUSSION

Our conservative lower limit on $M_2$ is well below the minimum secondary mass of $\sim 0.75 M_\odot$ required in recent theoretical predictions for steady LMXB sources (King et al. 1997). Imposing this condition of $M_2 \geq 0.75 M_\odot$ now yields a 95% confidence lower limit of $M_2 > 1.88 M_\odot$ and a 95% confidence upper limit of $i < 61^\circ$. This would make Cyg X-2 the heaviest neutron star mass measured to date, and thereby provide support for stiff equations of state for nuclear matter (e.g., Cook, Shapiro, & Teukolsky 1984) and would contradict the “softer” equations of state as described in, e.g., Brown & Bethe (1994). On the other hand, if we assume a maximum possible mass of the neutron star of $\sim 3.2 M_\odot$ (e.g., Rhoades & Ruffini 1974), we infer a 95% confidence upper limit of $M_2 < 1.28 M_\odot$ and a 95% confidence lower limit of $i > 45^\circ$. We note that the inclination constraints are more or less consistent with recent ellipsoidal model fits to a compilation of $BV$ photometric light curves (Orosz & Kuulkers 1998, in preparation).

The RXTE has discovered a maximum kHz QPO frequency at 1066–1171 Hz in eight persistent LMXBs, which, if interpreted as the orbital frequency of the last marginally stable orbit, implies neutron star masses of $2.0 \pm 0.2 M_\odot$ (Zhang, Strohmayer, & Swank 1997; see also Kaaret, Ford, & Chen 1997). Recently, kHz QPO have also been discovered in Cyg X-2 (Wijnands et al. 1998), so our mass estimate is in excellent agreement with that expected by Zhang et al. (1997). As they
noted, this would be consistent with current evolutionary scenarios for LMXBs, where neutron stars would be born at 1.4 $M_\odot$ but accrete at near-Eddington rates for $\sim 10^8$ yr (van den Heuvel & Bitzaraki 1995). Dynamical mass determinations of other persistent LMXBs with evolved secondaries (e.g., GX 1+4) will help to construct the distribution of neutron star masses and thereby allow new constraints to be set on the equation of state of nuclear-density matter.

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