SY Cnc, a case for unstable mass transfer?

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ABSTRACT

Intermediate-resolution (0.5–1 Å) optical spectroscopy of the cataclysmic variable (CV) SY Cnc reveals the spectrum of the donor star. Our data enable us to resolve the orbital motion of the donor and provide a new orbital solution, binary mass ratio and spectral classification. We find that the donor star has spectral-type G8 ± 2 V and orbits the white dwarf with \( P = 0.382 \pm 0.000003 \) d, \( K_2 = 88.0 \pm 2.9 \) km s\(^{-1}\) and \( V \sin i = 75.5 \pm 6.5 \) km s\(^{-1}\). Our values are significantly different from previous works and lead to \( q = M_2/M_1 = 1.18 \pm 0.14 \). This is one of the highest mass ratios known in a CV and is very robust, because it is based on resolving the rotational broadening over a large number of metallic absorption lines. The donor could be a slightly evolved main sequence or descendant from a massive star which underwent an episode of thermal time-scale mass transfer.

Key words: accretion, accretion discs – stars: individual: SY Cnc – novae, cataclysmic variables.

1 INTRODUCTION

Mass transfer in cataclysmic variables (CVs) is driven by angular-momentum-loss mechanisms. Magnetic braking is considered the main driver for orbital periods longer than \( \geq 3 \) hours, although its actual prescription is under debate (e.g. Ivanova & Taam 2003). As a result of mass transfer, the radius of the donor star is adjusted (1) on a thermal time-scale to try preserving thermal equilibrium and (2) on a dynamical time-scale to return to hydrostatic equilibrium. The competition between the changing stellar and Roche lobe radii sets the mass-transfer rate and hence its stability. For large mass ratios, the binary could be unstable against rapid mass transfer and a common envelope may ensue (King 1988).

SY Cnc is one of the brightest Z Cam-type dwarf novae, exhibiting regular outbursts every \( \sim 27 \) days. Shafter (1983) reported an orbital period \( P = 0.380 \pm 0.001 \) d and \( q = M_2/M_1 = 1.13 \pm 0.35 \) which was interpreted as evidence for unstable mass transfer. Unfortunately, \( q \) was derived indirectly using observed properties of the Hα emission line, and this method is not entirely reliable because the accretion disc’s emissivity is often found to be non-axisymmetric and contaminated by hotspots. The best way to constrain \( q \) is by combining the radial velocity semi-amplitude of the donor star \( K_2 \) with the rotational broadening of its absorption lines \( V \sin i \) (Wade & Horne 1988). The issue of the high \( q \) value was revisited by Smith et al. (2005) who measured \( K_2 = 127 \pm 23 \) km s\(^{-1}\) from a map of the Na\(\text{i} \) infrared (IR) doublet. However, the poor spectral resolution hindered a direct determination of \( V \sin i \), and hence \( K_2 \) was combined with \( K_1 \) (from the wings of the Hα line; Shafter 1983) to yield a revised \( q = 0.68 \pm 0.14 \). They also classify the donor star as M0, which must be substantially evolved in order to fill its 9.1-h Roche lobe.

Here, we present new higher resolution spectra of SY Cnc demonstrating that the spectrum of the donor star is clearly detected at optical wavelengths. We update the orbital parameters and present the first determination of the rotational broadening of the donor star, which removes the lingering uncertainty on the true mass ratio. We also find that the spectrum of the donor is best fitted by a late G star and discuss the observed properties in the light of mass-transfer stability and the evolution of SY Cnc.

2 OBSERVATION AND DATA REDUCTION

SY Cnc was observed over several nights between 1992 and 2008 using the Intermediate Dispersion Spectrograph attached to the 2.5-m Isaac Newton Telescope (INT) at the Observatorio del Roque de Los Muchachos. The 27 spectra were always obtained in the Hα region but using three gratings and slightly different instrumental settings (slit widths and central wavelengths), which resulted in spectral resolutions in the range 25–70 km s\(^{-1}\). The nights were allocated to various scientific programmes, and hence only a few spectra of SY Cnc were obtained per night. A log of the observations is presented in Table 1. Spectra of the stellar templates 61 Cyg A and B (K5V and K7V) were also observed during the 2008 run for the purpose of radial velocities and rotational broadening analysis. In addition, eight templates of spectral-types G6–M0V were collected during the 2003 campaign and another K5V in 1999.
level, we performed a Monte Carlo simulation. Synthetic $\chi^2$ periodograms were computed from a large population ($10^5$) of velocities randomly picked from a white-noise distribution and with identical time sampling as our data. A $4\sigma$ significance level is defined by the 99.99 per cent of the computed $\chi^2$ values, and this is indicated in Fig. 1 by a horizontal dashed line. Most of the peaks between frequencies 2.5 and 2.7 d$^{-1}$ are under the line, and hence periods in the range 0.37–0.40 d are significantly above noise at the 99.99 per cent level. The two deeper peaks correspond to 0.3824 and 0.3837 d and have $\chi^2 = 1.0$ and 2.3, respectively, for 24 degrees of freedom. A $4\sigma$ significance level around the minimum peak will exclude the second peak (Lampton, Margon & Bowyer 1976), and hence we can conclude that 0.3824 d is by far the most significant period. A least-squares sine-wave fit to the radial velocities, using $P = 0.3824$ d as input parameter, yields the following parameters:

$$\gamma = -0.2 \pm 2.5 \text{ km s}^{-1}$$
$$P = 0.3823753 \pm 0.0000003 \text{ d}$$
$$T_0 = 2451300.254 \pm 0.002$$
$$K_2 = 88.0 \pm 2.9 \text{ km s}^{-1},$$

where $T_0$ corresponds to the Heliocentric Julian date of 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 61 Cyg A that we take as $-64.3 \pm 0.9$ km s$^{-1}$ (Wilson 1953). Note that a sine-wave fit fixing $P = 0.3837$ d also yields $K_2 = 87.3 \pm 3.3$ km s$^{-1}$, an indication that our $K_2$ value is robust and its error realistic, irrespective of the true value of the orbital period. The same is found when other peaks around the minimum are taken.

Fig. 2 displays the radial velocity points folded on our favoured orbital period $P = 0.3823753$ d together with the best sine fit

![Figure 2](https://academic.oup.com/mnras/article-abstract/399/3/1534/1075876/1)

**Figure 2.** Radial velocity curve folded on $P = 0.3823753$ d. The best sine-wave solution is overplotted.
solution. Our \( K_2 \) velocity disagrees with the one reported by Smith et al. (2005) which was obtained using the 8190-Å Na i doublet. We note that the Na i doublet can be quenched by heating effects, as opposed to the metallic lines used by us (Martin et al. 1989). If this were the case, the light centre of the Na i lines would be displaced towards the back side of the star. The effects of irradiation can be estimated using the \( K \)-correction approach of Wade & Horne (1988) \( \Delta K_2/K_2 = f(r_2/a) (1 + q) \), where \( \Delta K_2 \) is the increment in \( K_2 \) velocity due to irradiation, \( r_2 \) is the radius of the donor star, \( a \) is the binary separation and \( f \) is the fractional displacement of the absorption line’s site with respect to the centre of mass of the star. In the extreme case, when the Na i absorption is completely suppressed from the irradiated hemisphere, \( f = 4/(3\pi) \). Thus, replacing \( r_2/a \) by Eggleton’s equation (Eggleton 1983) and adopting \( q = 1.18 \) (see the next section), we find \( \Delta K_2 = 32 \) km s\(^{-1} \). This difference is just enough to accommodate Smith et al.’s value with ours, for maximum quenching of the Na i lines. Therefore, we conclude that Smith et al.’s \( K_2 \) is likely a significant overestimate due to irradiation while our value is much less affected by these effects.

4 THE ROTATIONAL BROADENING AND SPECTRAL CLASSIFICATION

In order to measure the rotational broadening of the donor’s absorption features, we have focused on the 10 highest resolution spectra gathered during the 2003 campaign. We broadened the G6-M0 templates from 5 to 100 km s\(^{-1} \) in steps of 5 km s\(^{-1} \) using a Gray profile (Gray 1992) and continuum limb-darkening coefficients appropriate for every spectral type and our wavelength range. The broadened templates were multiplied by factors \( f < 1 \), to account for the fractional contribution to the total light. These were subsequently subtracted from the Doppler-corrected average of SY Cnc, obtained using our orbital solution above. The optimal broadening, based on a \( \chi^2 \) test on the residuals, is always found in the range 77–80 km s\(^{-1} \). The mean of these determinations is 78.4 \( \pm 3.5 \) km s\(^{-1} \). The quoted error corresponds to 1σ and has been estimated by fitting a cubic function to the \( \chi^2 \) versus \( V \sin i \) curve and searching for \( \chi^2_{\text{min}} + 1 \).

A potential source of systematics in this calculation is the assumption of continuum limb-darkening coefficient because absorption lines in late-type stars are expected to have smaller core limb-darkening coefficients than the continuum (Collins & Truax 1995). We have tested this by repeating the above analysis using zero limb darkening as a secure lower limit, and obtain \( V \sin i = 72 \pm 3 \) km s\(^{-1} \). Therefore, we decided to adopt 75.5 \( \pm 6.5 \) km s\(^{-1} \) as a conservative value for \( V \sin i \) hereafter. The minimum \( \chi^2 \) also constrains the donor’s spectral type to G9-K3V. The same analysis was independently performed using the lower resolution data from 1999 and 2008, which yield consistent results at 80 \( \pm 5 \) and 77 \( \pm 5 \) km s\(^{-1} \), respectively. In the latter case, the K5V template produces a lower minimum \( \chi^2 \) than the K7V, an indication that the donor star is earlier than K5.

To further constrain the spectral type, we employed a set of high-resolution (\( R = \lambda/\Delta \lambda = 55000–110000 \)) spectra covering G0-K7V from Eucvillon et al. (2004, 2006) and Montes & Martín (1998). These are HD 39091 (G0V), HD 30495 (G1.5V), HD 43162 (G6.5V), HD 69830 (K0V), HD 17925 (K1.5V), HD 222237 (K3V), HD 216803 (K4V) and HD 157881 (K7V). These stars have very accurate stellar parameters \( \log g, T_{\text{eff}} \) and metallicities, so that they can provide a more robust spectral-type classification. These were downgraded to the instrumental resolution of the 2008 INT data and broadened using our \( V \sin i \) estimate. Fig. 3 displays the \( \chi^2 \) of the optimal subtraction as a function of the template’s spectral type. The minimum is found for G6.5V and K0V, and thus we classify the donor star as a G8 \( \pm 2 \)V. This is again remarkably different from the M0 suggested by Smith et al. (2005), whereas it is in better agreement with the work of Harrison, Osborne & Howell (2004) who propose an early G star based on IR spectra. Fig. 4 presents the 2008 average spectrum of SY Cnc, Doppler-corrected in the rest frame of the donor star, together with one of the best templates. The latter must be scaled by a factor of 0.42 \( \pm 0.02 \) to match the depth of the absorption features in SY Cnc, and hence we conclude that the donor star contributes 42 per cent to the total flux in the \( H \alpha \) region.
5 DISCUSSION

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

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

This uses Eggleton’s expression for the effective radius of the Roche lobe (Eggleton 1983), which is more accurate than Paczyński’s approximation (Paczyński 1971). Substituting our values of $K_2$ and $V \sin i$ into equation (1), we find $q = 1.18 \pm 0.14$, where the error has been estimated using a Monte Carlo simulation. The input parameters $V \sin i$ and $K_2$ have been picked up randomly from normal distributions whose mean and sigma correspond to the observed values, and the process is repeated $10^5$ times. This is one of the highest, accurately measured, mass ratios in a CV, only comparable to V363 Aur with $q = 1.17 \pm 0.07$ (Thoroughgood et al. 2004).

For instance, the 7.10 edition of the Ritter & Kolb catalogue (Ritter & Kolb 2003) lists seven systems in 731 entries with $q > 1$. However, only V363 Aur and AC Cnc possess robust $q$ values because these are derived through a measurement of $K_2$ and $V \sin i$. The remaining five should be regarded as tentative, given the difficulty in deriving stellar masses in the absence of donor stellar features.

Theoretical studies of binary evolution show that stable mass transfer depends on both the thermal and dynamical responses of the donor star to mass loss. This is described by the thermal and adiabatic radius–mass exponents, computed for the case of zero-age main-sequence (ZAMS) donor stars (e.g. Politano 1996). When compared with the tidal radius–mass exponent (i.e. the logarithmic derivative of the Roche lobe radius with respect to the donor mass), they define a critical mass ratio for stable mass transfer. The radius–mass exponents, in turn, depend on the donor’s mass, so a combination of $(q, M_2)$ values is required to fulfill the condition for stable mass transfer.

SY Cnc presents a remarkable case because of its high (and accurate) mass ratio which places it close to the absolute upper limit of mass-transfer stability computed by Politano (1996). Fig. 5 shows the critical mass ratio curves for dynamical (solid line) and thermal stability (dashed line) as a function of the donor mass, updated after Figs. 1 and 2 from Smith & Vande Putte (2006).

SY Cnc to lie in the stable mass-transfer region (i.e. below the two curves), our central value $q = 1.18$ yields $M_2 \sim 0.77–1.54 M_\odot$. This would imply a white dwarf mass $M_1 \sim 0.65–1.31 M_\odot$ and, since $M_1 \sin^3 i = (1 + q^3) P K_2^2/2\pi G = 0.13 \pm 0.02 M_\odot$, then $i \sim 26–38^\circ$. However, the theoretical stability limits are computed under the assumption of ZAMS donor stars which is not necessarily true. Donor stars in CVs have on average later spectral types than field main-sequence stars, an indication of radius expansion (e.g. Knigge 2006). In particular, Beuermann et al. (1998) showed that donor stars with $P_{\text{orb}} \gtrsim 5–6$ h were likely nuclear-evolved at the start of mass transfer. This alters the helium-to-hydrogen composition and hence the response of the star to mass loss. Therefore, the critical mass ratios shown in Fig. 5 should be regarded as mere indicative limits.

Our determination of the spectral type also provides a new ingredient to constrain the evolution of the donor star in SY Cnc. A G8 ZAMS has $M_2 = 0.81 M_\odot$ which would place it reasonably well within the stability region. A donor with such mass would fill its Roche lobe in $\simeq 87$ per cent of its $9.1$-h Roche lobe. The conclusion seems to be that the companion star is a slightly evolved main sequence, in contrast with previous claims by Smith et al. (2005).

Alternatively, SY Cnc could be descending from a progenitor binary with a more extreme mass ratio which underwent a phase of thermal time-scale mass transfer. The importance of this evolutionary path has been addressed by several papers (e.g. Schenker & King 2002; Podsiadlowski, Han & Rappaport 2003; Kolb & Willems 2005) and successfully explains the cooler-than-main-sequence behavior of SY Cnc. A detection of nuclear processed material in ultraviolet spectra of SY Cnc would clarify the evolutionary history of SY Cnc and whether it is the outcome of a thermal mass-transfer episode. Further, more higher resolution observations will provide better constraints on $V \sin i$, $K_2$, the stellar masses and the evolution of the donor star in this important CV.

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Figure 5. Binary mass ratio versus donor mass. The solid and dashed lines represent the critical mass ratio for adiabatic (dynamical) and thermal mass-transfer stability, respectively, for ZAMS donor stars. The thick horizontal lines mark our limits to $q$. © 2009 The Authors. Journal compilation © 2009 RAS, MNRAS 399, 1534–1538
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