EMISSION FROM THE SECONDARY STAR IN THE OLD CV WZ SGE

D.Steeghs, T.Marsh, C.Knigge
Department of Physics & Astronomy, University of Southampton, Highfield, Southampton SO17 1BJ, UK
P.F.L.Maxted
Astrophysics Group, School of Chemistry & Physics, Keele University, Staffordshire, ST5 5BG, UK
E.Kuulkers
Space Research Organization Netherlands, Sorbonnelaan 2, 3584 CA Utrecht, NL
Astronomical Institute, Utrecht University, P.O. Box 80000, 3508 TA Utrecht, The Netherlands
W.Skidmore
School of Physics & Astronomy, University of St.Andrews, North Haugh, St.Andrews, Fife KY16 9SS, UK

submitted to ApJ Letters

ABSTRACT

We present the first detection of the mass donor star in the cataclysmic variable WZ Sge. Phase resolved spectroscopy reveals narrow Balmer emission components from the irradiated secondary star during the 2001 outburst. Its radial velocity curve indicates a systemic velocity of \(-72 \pm 3\, \text{km/s}\) and an apparent velocity amplitude of \(K_{\text{app}} = 493 \pm 10\, \text{km/s}\). Doppler tomography reveals a highly asymmetric accretion disc including a significant bright spot contribution 20 days into the outburst. We estimate the primary radial velocity \(K_1\) using a center of symmetry method and find \(K_{\text{app}} = 37 \pm 5\, \text{km/s}\). Accounting for the likely systematic errors affecting both \(K_1\) and \(K_2\) measurements, we conservatively derive \(508 < K_2 < 585\, \text{km/s}\) and \(K_1 < 37\, \text{km/s}\). This implies a massive white dwarf with \(M_1 > 0.77\, M_\odot\). A non-degenerate mass donor, implying WZ Sge has not yet evolved through its minimum orbital period, is not ruled out by our observations. This would require an improved estimate of \(K_1\). Together with the measured phase offset between bright spot eclipse and inferior conjunction of the secondary star, we can bracket the allowed mass ratio \((q = M_2/M_1)\) to lie between 0.040 and 0.073. This provides a firm upper limit to the mass of the secondary of \(M_2 < 0.10\, M_\odot\).

Subject headings: novae, cataclysmic variables — accretion, accretion discs — stars, individual (WZ Sge)

1. INTRODUCTION

In cataclysmic variables (CVs), a white dwarf accretes from a low mass secondary star through Roche-lobe overflow. Angular momentum loss drives the binary system to progressively shorter orbital periods until the donor star becomes degenerate. Further mass exchange then results in an increase of the orbital period of the system, which leads to a predicted minimum period of \(\sim 70\, \text{minutes}\) through which all CVs should eventually evolve (e.g. Kolb & Baraffe 1999). With an orbital period of only 82 minutes, WZ Sge is one of the very few candidates among the hundreds of known CVs that may have already evolved past this minimum period (Patterson 1998). Its quiescent magnitude of \(V \sim 15.5\) and distance of approximately 45 pc (Thorstensen 2001, astrometric parallax, private communication), make it one of the lowest luminosity CVs known. Despite the accretion light being faint enough for the white dwarf to dominate in quiescence, infrared spectroscopy has so far not shown any signs of the mass donor star (Littlefair et al. 2000). Instead of the 3-5 magnitude outbursts that longer period dwarf novae tend to undergo every few weeks to months, WZ Sge’s outbursts have an amplitude of 7-8 magnitudes and recur on a timescale of roughly 33 years. These facts suggest that WZ Sge is a highly evolved system, in which gigayears of mass transfer have converted a main sequence secondary star to a degenerate brown dwarf. However, the absence of any direct signatures of the secondary have prevented a robust determination of the system parameters of this unique system.

On July 23rd 2001, amateur observers reported a sudden and rapid brightening of WZ Sge (Ishioka et al. 2001), indicating another outburst had started, around 23 years after the previous outburst in 1978, and therefore around 10 years earlier than anticipated. Here we present phase resolved spectroscopy of WZ Sge in the first weeks of its 2001 outburst, which reveals a clear signature of the irradiated mass donor star for the first time.

2. OBSERVATIONS AND REDUCTION

The phase resolved spectra of WZ Sge were obtained with the 2.5m Isaac Newton Telescope (INT) and the 4.2m William Hershel Telescope (WHT) on the island of La Palma. The intermediate dispersion spectrograph on the INT in conjunction with the R1200B grating delivered a wavelength coverage of 3800-4950Å at 0.48Å/pixel using an EEV CCD detector. On August the 6th, 1022 spectra were obtained in total on the INT using 13 s exposures between 20:46 and 22:14 UT and 00:14 - 04:36 UT. On the WHT, the dual arm ISIS spectrograph was used, covering 4220-4975Å on the blue arm at 0.22Å/pixel (EEV CCD) and 6380-6775Å at 0.4Å/pixel on the red arm (TEK CCD). The slit width was adjusted in order to project to 2-3 pixels on the CCD. Since no sufficiently bright comparison star was available that could be aligned along the slit, the slit was always kept close to the parallactic angle. On August 13th, 541 red arm spectra using 10 s exposures.
and 233 blue arm 15 s exposures were acquired between 20:50 and 23:03 UT. Frames were de-biased using the over-
scan areas of the CCDs. A normalised median of tungsten
exposures was then constructed for each night and used to
carry out flat field correction. Finally, the WZ Sge spectra
were optimally extracted (Marsh, 1989). Regular arc lamp
exposures allowed us to establish an accurate wavelength
scale for each spectrum through interpolation between the
two nearest arc spectra. The individual spectra were nor-
malised to the continuum level using a spline fit to selected
continuum regions.

3. DATA ANALYSIS

In Figure 1 we present the average normalised spectrum
of WZ Sge on August 6th and 13th. Both observations oc-
curred during the initial slow decline phase of the outburst
with approximate V magnitudes of 10.0 on the 6th (13
days into the outburst) and 10.5 on the 13th. For com-
parison, V ∼ 8 at outburst maximum on July 24th (we refer
to the AAVSO\(^2\) and VSNET\(^2\) webpages for extensive
visual magnitude estimates throughout the outburst).

The spectrum of WZ Sge in outburst is dominated by
complex Balmer and Helium line profiles. Except for the
HeII/Bowen blend emission complex, all lines show very
deep and phase dependent absorption components on top
of double peaked emission. In most cases the absorption
goes well below the continuum level, except in H\(_\alpha\). We use
the orbital ephemeris of Patterson et al. (1998), hereafter
P98, to calculate the orbital phases throughout this Letter.
The ephemeris is a small improvement to the often-used
Robinson, Nather and Patterson (1978; hereafter RNP)
ephemeris amounting to a difference of ∼0.001 cycles at
the time of the current outburst. The ephemeris zerpoint
is based on the sharp eclipses of the bright spot and does
not correspond to the inferior conjunction of the secondary
star. Spruit & Rutten (1998), hereafter SR, for example
derive a phase offset of −0.041 ± 0.003 between the RNP
ephemeris and the mid-point of the accretion disc eclipse.
We will address this phase offset in Section 3.3.

3.1. Balmer emission from the secondary

The time dependent H\(_\alpha\) line emission as observed on
August 13th is displayed in Figure 2 as a trailed spectrogram.
The double-peaked line profile is highly phase dependent
and asymmetric. Apart from the two double peaks reflect-
ing emission from the accretion disc, a narrow emission
component moves through the peaks and produces a clear
S-wave on the orbital period. On much shorter timescales,
rapid transient features can be seen crossing the line pro-
file, almost always from blue to red. An example is the
narrow emission feature rapidly crossing in a few minutes
around phase 0.55. During quiescence, the line profiles of
WZ Sge are dominated by the double-peaked disc emission
as well as a strong contribution from the bright spot (SR,
Skidmore et al. 2000). However, the S-wave in our out-
burst data is much narrower and traces a near sinusoidal
radial velocity curve. Such narrow, sinusoidal S-waves are
commonly observed in accreting binaries and are generally
attributed to line emission from an irradiated secondary
star. Provided a sufficient amount of ionising radiation is
received from the compact object and the inner disc re-
regions, optical line emission from the exposed parts of the
secondary star is produced (e.g. Marsh & Horne 1990,
Harlaftis et al. 1996, Steeghs & Casares, 2001). This in-
terpretation is supported by the phasing of the S-wave,
which corresponds closely to the expected phasing of the
secondary in WZ Sge. In addition, its strength is highly
phase dependent, reaching maximum emission around or-
bital phase 0.5, as expected from an irradiated Roche lobe
filling star. Given the complexity of the line profiles, we
decided to use Doppler tomography (Marsh & Horne 1988)
to isolate and study the nature of the emission line com-
ponents.

3.2. The systemic velocity

Doppler tomography requires the systemic velocity (\(\gamma\))
to be supplied as input to the reconstruction algorithm.
Gilliland et al. (1986) measured \(\gamma = -72 \pm 3\) km/s using
radial velocities derived from the H\(_\alpha\) line wings. Skid-
more et al. (2000) derive a mean systemic velocity of
\(-78 \pm 9\) km/s based on radial velocity curves of several
emission lines. Both of these determinations rely on the
assumption that the emission line velocities reflect the mo-
tion of the compact object. On the other hand, SR used
Doppler tomography techniques to determine the systemic
velocity, by minimising the residuals between observed
and predicted data. They found \(\gamma = -71 \pm 3\) km/s.

We chose to measure the systemic velocity directly us-
ing the detected S-wave from the secondary star, since
its radial velocity is displaced by the true systemic velo-
city of the binary system irrespective of the properties of
the accretion flow around the white dwarf. To this end
we calculated a series of preliminary Doppler maps from
the observed data using a filtered back projection method
(Marsh 2001). For each map, a different systemic velocity
was assumed ranging from 0 to -110 km/s in 10 km/s steps.
The Doppler maps then provide the strength of all S-waves
on the orbital period in the data with a given amplitude
and phase, which is maximised when the correct value for
\(\gamma\) is used. We measured the strength of the secondary star
emission in each Doppler image, and found that a well de-
fined maximum was achieved for \(\gamma = -74 \pm 3\) km/s using
the observed H\(_\alpha\) emission. The same analysis applied to
the H\(_\beta\) emission also reveals a clear secondary star con-
tribution which is maximised for \(\gamma = -69 \pm 3\) km/s. We
thus use a systemic velocity of \(\gamma = -72\) km/s throughout
this Letter, based on the mean of the H\(_\alpha\) and H\(_\beta\) values.
Our systemic velocity, based on the radial velocity curve of
the mass donor star, is in close agreement with the values
determined from the disc emission lines.

3.3. The radial velocity of the secondary

The final Doppler tomogram illustrating the distribu-
tion of H\(_\alpha\) emission on August 13th is displayed in Figure
2. The tomogram was constructed from a regularised fit to
the observed line profiles, using maximum entropy regular-
isation (Marsh 2001). The secondary star emission maps
to a sharp spot with a FWHM of ∼130 km/s compared to a
resolution element of 36 km/s. Maximum emission occurs

1 http://www.aavso.org
2 http://www.kusastro.kyoto-u.ac.jp/vsnet/
at \( V_r = -140 \pm 10 \text{ km/s} \), \( V_\alpha = 470 \pm 10 \text{ km/s} \) as derived from a 2D Gaussian fit. If the data was folded on the correct orbital ephemeris, emission from the mass donor should appear on the positive \( V_\alpha \)-axis, corresponding to the radial velocity (\( K_2 \)) of the mass donor star. The emission of the secondary thus allows us to calculate the phase of inferior conjunction relative to the photometric ephemeris of P98. If we assume that the center of the H\( \alpha \) emission corresponds to the center of the mass donor we can derive a phase offset of \(-17 \pm 1^\circ \) (\( \Delta \phi_{\text{spot}} = -0.046 \pm 0.003 \) in terms of orbital phase) and an apparent radial velocity amplitude of \( K_{2_{\text{app}}} = 493 \pm 10 \text{ km/s} \). Our value for the phase offset appears slightly larger than that of SR based on the disc eclipse during quiescence, but is still within 2 sigma of their value. For comparison, the same analysis applied to the Doppler maps of the H\( \beta \) and H\( \gamma \) emission leads to identical phase offsets for both lines (\( 17^\circ \)) and radial velocities of \( 478 \pm 10 \text{ km/s} \) (H\( \beta \)) and \( 479 \pm 10 \text{ km/s} \) (H\( \gamma \)) respectively. There is no evidence for any secondary star emission in the He\( l6678 \), He\( II4686 \) or Bowen blend transitions, indicating that the secondary star is exposed to relatively soft ionising radiation. The quoted uncertainties on these values does not include the systematic errors that affect both \( K_2 \) and the phase offset because of the unknown distribution of the line emission across the Roche lobe (c.f. Steeghs & Casares, 2001). If the line emission is biased towards either the left or right hemisphere of the lobe, a corresponding bias to the derived phase offset would be introduced. Given that only the front part of the Roche lobe is irradiated, and that no intrinsic line emission from the secondary is observed during quiescence, the apparent radial velocity amplitude of the emission \( K_{2_{\text{app}}} \) will be smaller than the true radial velocity \( K_2 \) of the secondary. The observed line emission must originate somewhere between the L1 point and the terminator that separates the irradiated part of the Roche lobe from its unirradiated side. The conservative assumption that all emission originates at the terminator implies that the smallest possible correction between \( K_{2_{\text{app}}} \) and \( K_2 \) is around 3\%. This was derived from Roche geometry calculations across the allowed mass ratio range. Thus our detection of H\( \alpha \) emission at 493 km/s implies \( K_2 > 508 \text{ km/s} \). On the other hand, the observed velocities cannot be smaller than the velocity of the L1 point, which leads to an upper limit of \( K_2 < 585 \text{ km/s} \). Here we have again allowed for a wide range of mass ratios consistent with \( M_1 < 1.4M_\odot \).

### 3.4. The radial velocity of the primary

Armed with a good estimate for the radial velocity amplitude of the secondary star, the mass ratio \( q = M_2/M_1 = K_1/K_2 \) of the binary can be determined if the radial velocity of the primary (\( K_1 \)) is also known. Gilliland et al. (1986) obtained an estimate of \( K_1 = 48 \pm 6 \text{ km/s} \) from the radial velocities of both H\( \alpha \) line wings and peaks. However, the radial velocity curves show phase offsets with respect to the absolute ephemeris which indicate that these radial velocity curves must be severely distorted. This is a common situation in CVs, and may not be surprising given the strong bright spot emission that is present in WZ Sge during quiescence. Mason et al. (2000) also measured emission line velocities using a wide range of spectral lines in the optical and infrared regime. They found velocity amplitudes between 46 and 121 km/s and large phase offsets depending on the excitation potentials of the lines. They concluded that a varying degree of bright spot contamination distorts the radial velocity curves of the emission lines.

SR used a different approach and attempted to find the center of symmetry of the disc emission in the Doppler map at a given velocity, ignoring areas that are affected by the bright spot. They found that at large velocities the center of symmetry seems to converge on \( K_{1_{\text{app}}} = 40 \pm 10 \text{ km/s} \), even though the phase offset is still considerable (\( 50^\circ \)). We applied a similar method to the outburst H\( \alpha \) tomogram, and find a convergence to a center of symmetry at \( K_{1_{\text{app}}} = 37 \pm 5 \text{ km/s} \) at high velocities (1200-1500 km/s) before noise starts to dominate. The optimal center of symmetry, like in the case of SR, is offset from the expected position of the white dwarf corresponding to a phase shift of \( 60^\circ \). If we force the center of symmetry to be phased with the white dwarf while minimising the residuals at areas not affected by the bright spot, we find \( K_{1_{\text{app}}} = 40 \pm 5 \text{ km/s} \). Although the formal uncertainty of this optimal center of symmetry is only a few km/s, our methods may be affected by systematic errors due to the fact that we are relying on a complicated emission structure to reflect the motion of the white dwarf. As indicated by our Doppler images, the accretion flow is highly asymmetric, and a significant amount of distortion may be expected. We therefore consider 37 km/s to be an upper limit to the true radial velocity amplitude of the white dwarf.

The bottom-right panel of Figure 2 plots the asymmetric part of the H\( \alpha \) emission, after the symmetric part with respect to the optimal center of symmetry was subtracted. Significant asymmetries are clearly present, and the resemblance between our outburst map and the quiescent H\( \alpha \) Doppler map of SR is both striking and surprising. It appears a substantial contribution to the line flux originates from the bright spot region. It has been proposed in the past (Smak 1996; Hameury, Lasota & Hure, 1997), that heating of the secondary during outburst may lead to an increase in the mass transfer rate and thereby prolong the outburst duration. We refrain from speculating about the nature of the disc asymmetries until a more thorough comparison with other outburst tomography throughout the 2001 campaign can be made.

#### 3.5. The system parameters

White dwarf mass estimates have led to a wide range of published white dwarf masses in WZ Sge ranging from 0.3\( M_\odot \) to 1.2\( M_\odot \). Our lower limit to the radial velocity of the secondary star (\( K_2 > 508 \text{ km/s} \)) leads to a mass function of:

\[
\begin{align*}
 f(M_1) = \frac{PK_2^3}{2GM_1} = \frac{M_1 \sin^3 \iota}{(1+q)^2} > 0.77M_\odot
\end{align*}
\]

Thus the low white dwarf mass values of, for example, Smak (1993), RNP and Cheng et al. (1997), are not compatible with our \( K_2 \) measurements, and a more massive white dwarf is required. With \( K_2 > 508 \text{ km/s} \) and \( K_1 < 37 \text{ km/s} \) we have \( q < 0.073 \) implying \( M_2 < 0.10M_\odot \) since \( M_1 < 1.4M_\odot \). Thus, a non-degenerate secondary star is formally not yet ruled out. However, the lack of
any contribution of the mass donor to the J and K bands (Littlefair et al. 2000) is difficult to reconcile with a late main sequence mass donor around $\sim 0.1 M_\odot$. Even for highly evolved main sequence stars, the predicted J and K band magnitudes are significantly too bright (e.g., Leggett et al. 2001). If, as expected for a system that has evolved through the period minimum, the secondary star is in fact a degenerate star with $M_2 < 0.076 M_\odot$, $K_1$ must be less than 28 km/s. This clearly illustrates the need for an accurate determination of the radial velocity of the primary in WZ Sge. Given that the accretion flow is clearly asymmetric both during quiescence as well as outburst, this may only be possible through the use of photospheric white dwarf line velocities. Cheng et al. (1997) did not detect a systematic velocity shift in their HST data of WZ Sge.

The measured phase offset ($\Delta\phi_{\text{spot}}$) between inferior conjunction of the secondary and bright spot eclipse provides another constraint to the allowed mass ratio range. We calculated gas stream trajectories in order to determine the predicted $\Delta\phi_{\text{spot}}$ as a function of mass ratio and disc radius. Allowing for the uncertainty in disc radius measurements, we can then rule out mass ratios smaller than $q < 0.040$ since the predicted phase offset would be larger than 0.049 compared to our value of $\Delta\phi_{\text{spot}} = 0.046 \pm 0.003$, and $\Delta\phi_{\text{spot}} = 0.041 \pm 0.003$ as derived by SR.

4. DISCUSSION

We have detected Balmer emission originating from the irradiated mass donor in the CV WZ Sge during the second and third weeks of its 2001 outburst. This is the first time a direct detection of the low mass secondary in WZ Sge has been made. The Doppler maps of WZ Sge on August 13th are markedly different from those in the first few days of the outburst. Orbit resolved spectroscopy on July 28th, only 5 days into the outburst revealed an accretion disc dominated by two spiral arms (Steeghs et al. 2001), and no sign of any secondary star emission in either H$\beta$, HeI or HeII (H$\alpha$ was not observed). By August 13th, not only is the secondary star present in emission, the accretion flow also has made a major transition. The disc emission is dominated by a strong extended bright spot, very similar to its quiescent structure even though the system is still 5 magnitudes brighter than its quiescent level. The implications of this in terms of varying mass transfer and bright spot contribution throughout the 2001 outburst will be pursued in a future paper.

A reliable determination of the component masses in WZ Sge awaits an accurate determination of the radial velocity of the white dwarf. Accounting for the possible systematic errors affecting both $K_1$ and $K_2$ measurements, we conservatively derive $508 < K_2 < 585$ km/s, $K_1 < 37$ km/s and $0.040 < q < 0.073$. In terms of component masses, this corresponds to $0.77 < M_1 < 1.4 M_\odot$, while $M_2 < 0.10 M_\odot$.

DS is supported by a PPARC Fellowship. The William Herschel and Isaac Newton telescopes are operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias. Many thanks to the Isaac Newton Group staff for obtaining part of the data through the ING service programme. We would also like to thank the many colleagues and amateur observers who are contributing to the WZ Sge campaign during its 2001 outburst.

REFERENCES

Cheng, F.H., Sion, E.M., Sokody, P., Huang, M., 1997, ApJL, 484, 149
Gilliland, R.L., Kemper, E., Suntzeff, N., 1986, ApJ, 301, 252
Hameury, J.M., Lasota, J.P., Hure, J.M., 1997, MNRAS, 287, 937
Harlaftis, E.T., Horne, K., Filippenko, A.V., 1996, PASP, 108, 762
Ishioka, R., Uemura, M., Matsumoto, K.T., Yamaoka, H., 2001, IAUC 7669
Kolb, U., Baraffe, I., 1999, MNRAS 309, 1034
Leggett, S.K., Allard, F., Geballe, T.R., Hauschildt, P.H., Schweitzer, A., 2001, ApJ, 548, 908L
Littlefair, S.P., Dhillon, V.S., Howell, S.B., Ciardi, D.R., 2000, MNRAS, 313, 117
Marsh, T.R., 1989, PASP, 101, 1032
Marsh, T.R., 2001, in: Astrometry, Lecture Notes in Physics Series Volume 573, Springer Verlag
Marsh, T.R., Horne, K., 1988, MNRAS, 235, 269
Marsh, T., Horne K., 1990, ApJ, 349, 593
Mason, E., Skidmore, W., Howell, S.B., Ciardi, D.R., Littlefair, S., Dhillon, V.S., 2000, MNRAS, 318, 440
Patterson, J., 1998, PASP 110, 1132
Patterson, J., Richman, H., Kemp, J., Mukai, K., 1998, PASP, 110, 403
Robinson, E.L., Nather R.E., Patterson, J., 1978, ApJ, 219, 168
Skidmore, W., Mason, E., Howell, S.B., Ciardi, D.R., Littlefair, S., Dhillon, V.S., 2000, MNRAS, 318, 429
Smak, J., 1993, Act.Astr., 43, 101
Smak, J., 1996, in: Evans,A., Wood,J. Eds, IAU Coll. 185, Cataclysmic variables and related objects, Kluwer
Spruit, H., Rutten, R.G.M., 1998, MNRAS, 299, 768
Steeghs, D., Casares, J., 2001, ApJ, in press [astro-ph/0107343]
Steeghs, D., Marsh, T., Kuulkers, E., Skidmore, W., 2001, IAUC 7675
Fig. 1.— The average spectrum of WZ Sge on August the 6th (top) and August the 13th. Spectra are normalised to the continuum and the blue INT spectrum of August the 6th is displaced upwards by 0.4. Several prominent lines are labelled.
Fig. 2.— Top left: the observed Hα emission as a function of orbital phase on August 13th. Below, the corresponding Doppler map revealing the mass donor star in emission. Top right: the observed data after the mean spectrum was subtracted, highlighting the asymmetries in the accretion flow as well as the S-wave from the secondary. Bottom right is the asymmetric part of the Hα tomogram, obtained through subtraction of the symmetric component centered on the expected location of the white dwarf. The predicted location of the Roche lobe and ballistic gas stream is plotted for $q = 0.073$ ($K_2 = 508$ km/s, $K_1 = 37$ km/s) and $\Delta \phi_{\text{spot}} = 0.046$. 

$H\alpha$ 13/8/2001  mean subtracted

Velocity (km/s)  Velocity (km/s)