

EMISSION FROM THE SECONDARY STAR IN THE OLD CATAclySMIC VARIABLE WZ SAGITTAE

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ABSTRACT

We present the first detection of the mass donor star in the cataclysmic variable WZ Sagittae. 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 $-72 \pm 3 \text{ km s}^{-1}$ and an apparent velocity amplitude of $K'_2 = 493 \pm 10 \text{ km s}^{-1}$. Doppler tomography reveals a highly asymmetric accretion disk including a significant bright spot contribution 20 days into the outburst. We estimate the apparent primary radial velocity using the H α tomogram and find $K'_1 = 37 \pm 5 \text{ km s}^{-1}$. Accounting for the likely systematic errors affecting both K_1 and K_2 measurements, we conservatively derive $493 \text{ km s}^{-1} < K_2 < 585 \text{ km s}^{-1}$ and $K_1 < 37 \text{ km s}^{-1}$. The measured phase offset between bright spot eclipse and inferior conjunction of the secondary star brackets the allowed mass ratio ($q = M_2/M_1$) to lie between 0.040 and 0.075. These constraints imply a white dwarf with $M_1 > 0.70 M_\odot$ and a low-mass secondary with $M_2 < 0.11 M_\odot$. A nondegenerate mass donor, implying WZ Sge has not yet evolved through its minimum period, is therefore not ruled out by our observations. This would require an improved estimate of K_1 .

Subject headings: accretion, accretion disks — novae, cataclysmic variables — stars: individual (WZ Sagittae)

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 ~ 70 minutes through which all CVs should eventually evolve (e.g., Kolb & Baraffe 1999). With an orbital period of only 82 minutes, WZ Sagittae 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 (J. R. Thorstensen 2001, private communication) make it one of the lowest luminosity CVs known.

Instead of the 3–5 mag outbursts that longer period dwarf novae tend to undergo every few weeks to months, WZ Sge's outbursts have a much larger amplitude of 7–8 mag and recur on a timescale of roughly 33 yr. 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 (e.g., Patterson 1998). 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). On 2001 July 23, variable star observers reported a sudden and rapid brightening of WZ Sge (Ishiooka et al. 2001), indicating another outburst had started, around 23 yr after the previous outburst in 1978 and therefore around 10 yr 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 2.5 m Isaac Newton Telescope (INT) and the 4.2 m William Herschel 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 3800–4950 Å at $0.48 \text{ Å pixel}^{-1}$ using an EEV CCD detector. On August 6, 1022 spectra were obtained in total on the INT using 13 s exposures between 20:46 and 22:14 UT and 00:14 and 04:36 UT. On the WHT, the dual-arm ISIS spectrograph was used, covering 4220–4975 Å on the blue arm at $0.22 \text{ Å pixel}^{-1}$ (EEV CCD) and 6380–6775 Å at 0.4 Å pixel^{-1} on the red arm (Tek CCD). The slit width was adjusted in order to project to 2–3 pixels on the CCD and was always kept close to the parallactic angle.

On August 13, 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 debiased using the overscan areas of the CCDs. A normalized 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 normalized to the continuum level using a spline fit to selected continuum regions.

3. DATA ANALYSIS

In Figure 1, we present the average normalized spectrum of WZ Sge on August 6 and 13. Both observations occurred during the initial slow decline phase of the outburst with approximate V magnitudes of 10.0 on August 6 (13 days into the outburst) and 10.5 on August 13. For comparison, $V \sim 8$ at outburst maximum on July 24 (we refer to the American As-

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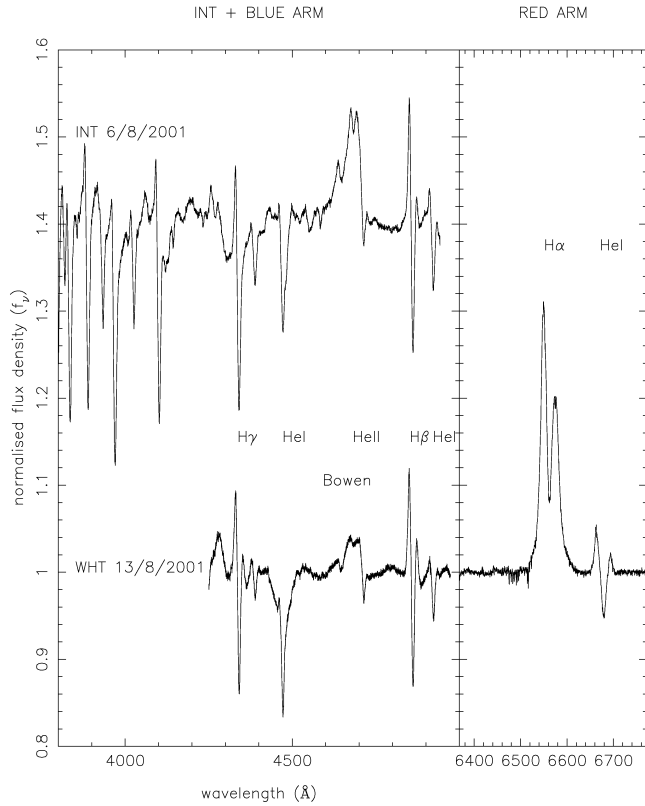


FIG. 1.—Average spectrum of WZ Sge on August 6 (*top*) and August 13 (*bottom*). Spectra are normalized to the continuum, and the blue INT spectrum of August 6 is displaced upward by 0.4. Several prominent lines are labeled.

sociation of Variable Star Observers⁶ and Variable Star Network⁷ Web pages 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 He II/Bowen blend emission complex, all lines show very deep and phase-dependent absorption components on top of double-peaked emission. 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 Robinson, Nather, & Patterson (1978, hereafter RNP) ephemeris amounting to a difference of ~ 0.001 cycles at the time of our observations. The ephemeris zero point 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 midpoint of the accretion disk eclipse.

3.1. Balmer Emission from the Secondary

The time-dependent H α line emission as observed on August 13 is displayed in Figure 2 as a trailed spectrogram. The double-peaked line profile is highly phase dependent and asymmetric. During quiescence, the line profiles of WZ Sge are dominated by the double-peaked disk emission as well as a strong contribution from the bright spot (SR; Skidmore et al. 2000). In our data, we can identify the double peaks from the disk as well as a broad emission component that resembles the ex-

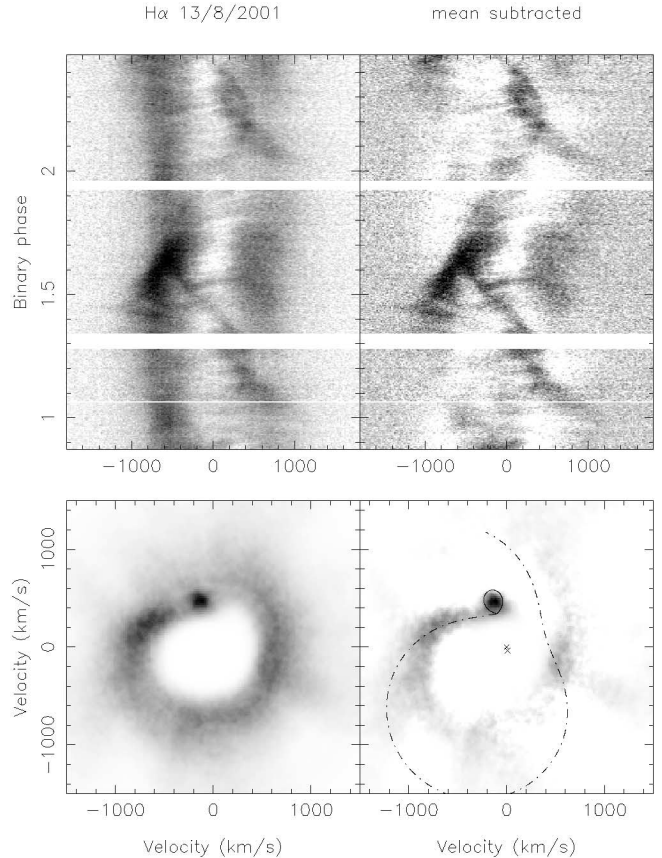


FIG. 2.—*Top left*: Observed H α emission as a function of orbital phase on August 13. *Bottom left*: Corresponding Doppler map revealing the mass donor star in emission. *Top right*: the observed data after the mean spectrum was subtracted, highlighting the asymmetries in the accretion flow as well as the s-wave from the secondary. *Bottom right*: Asymmetric part of the H α 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 $q = 0.075$ ($K_2 = 493 \text{ km s}^{-1}$, $K_1 = 37 \text{ km s}^{-1}$) and $\Delta\phi_{\text{spot}} = 0.046$.

pected emission signature from the bright spot. However, an additional narrow emission component is present, producing a clear s-wave on the orbital period.

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 ionizing radiation is received from the compact object and the inner disk regions, optical line emission from the exposed parts of the secondary star is produced (e.g., Marsh & Horne 1990; Steeghs & Casares 2001). This interpretation 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 orbital 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 components. Doppler tomography requires the systemic velocity (γ) to be supplied as input parameter. We measured the systemic velocity of WZ Sge using the radial velocity curve of the secondary star emission and find $\gamma = -72 \pm 2 \text{ km s}^{-1}$. This is in close agreement with the values determined from the disk emission ($-72 \pm 3 \text{ km s}^{-1}$ by Gilliland, Kemper, & Suntzeff 1986; $-71 \pm 3 \text{ km s}^{-1}$ by SR).

⁶ See <http://www.aavso.org>.

⁷ See <http://www.kusastro.kyoto-u.ac.jp/vsnet>.

3.2. Radial Velocity of the Secondary

The Doppler tomogram illustrating the distribution of H α emission on August 13 is displayed in Figure 2. The tomogram was constructed using maximum entropy regularization (Marsh 2001). The secondary star emission maps to a sharp spot with an FWHM of $\sim 130 \text{ km s}^{-1}$ compared to a resolution element of 36 km s^{-1} . Maximum emission occurs at $V_x = -140 \pm 10 \text{ km s}^{-1}$, $V_y = 470 \pm 10 \text{ km s}^{-1}$, as derived from a two-dimensional Gaussian fit. If the data was folded on the correct orbital ephemeris, emission from the mass donor should appear on the positive V_y -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 α emission corresponds to the center of the mass donor, we can derive a phase offset of $-17^\circ \pm 1^\circ$ ($\Delta\phi_{\text{spot}} = -0.046 \pm 0.003$ in terms of orbital phase) and an apparent radial velocity amplitude of $K'_2 = 493 \pm 10 \text{ km s}^{-1}$. Our value for the phase offset is larger than that of SR based on the disk eclipse during quiescence but is still within 2σ of their value. For comparison, the same analysis applied to the Doppler maps of the H β and H γ emission leads to identical phase offsets for both lines (17°) and apparent radial velocities of $478 \pm 10 \text{ km s}^{-1}$ (H β) and $479 \pm 10 \text{ km s}^{-1}$ (H γ), respectively. The quoted uncertainties on these values do 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 (see Steeghs & Casares 2001). 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 will be smaller than the true radial velocity K_2 of the secondary. On the other hand, the observed velocities cannot be smaller than the velocity of the L1 point, which leads to an upper limit of $K_2 < 585 \text{ km s}^{-1}$. Here we have allowed for a wide range of mass ratios consistent with $M_1 < 1.4 M_\odot$. We can thus conservatively conclude that $493 \text{ km s}^{-1} < K_2 < 585 \text{ km s}^{-1}$.

3.3. 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 $K_1 = 48 \pm 6 \text{ km s}^{-1}$ from the radial velocities of both H α line wings and peaks. However, the radial velocity curves show phase offsets with respect to the absolute ephemeris that indicate that these radial velocity curves must be severely distorted. This is a common situation in CVs (e.g., Stover et al. 1980) 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 large phase offsets depending on the excitation potentials of the lines and 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 disk emission in the Doppler map, ignoring areas that are affected by the bright spot. They found that the center of symmetry seems to converge on $K'_1 = 40 \pm 10 \text{ km s}^{-1}$ with a considerable phase offset (50°). We applied a similar method to the outburst H α tomogram and find a con-

vergence to a center of symmetry at $K'_1 = 37 \pm 5 \text{ km s}^{-1}$ at high velocities ($1200\text{--}1500 \text{ km s}^{-1}$) before noise starts to dominate. The optimal center of symmetry, as in the case of SR, is offset from the expected position of the white dwarf corresponding to a phase shift of 60° . Although the formal uncertainty of this optimal center of symmetry is only a few kilometers per second, 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. We therefore consider 37 km s^{-1} 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 α 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 α Doppler map of SR is both striking and surprising. It appears that 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 disk asymmetries until a more thorough comparison with other outburst tomography throughout the 2001 campaign can be made.

3.4. System Parameters

White dwarf mass estimates have led to a wide range of published white dwarf masses in WZ Sge ranging from 0.3 to $1.2 M_\odot$. Our lower limit to the radial velocity of the secondary star ($K_2 > 493 \text{ km s}^{-1}$) leads to a mass function of $f(M_1) = PK_2^3/2\pi G > 0.70 M_\odot$. 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. With $K_2 > 493 \text{ km s}^{-1}$ and $K_1 < 37 \text{ km s}^{-1}$, we have $q < 0.075$, implying $M_2 < 0.11 M_\odot$ since $M_1 < 1.4 M_\odot$. Thus, a nondegenerate 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 27 km s^{-1} . 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 be possible only through the use of photospheric white dwarf line velocities. Cheng et al. (1997) did not detect systematic Doppler shifts due to orbital motion of the white dwarf in their *Hubble Space Telescope* 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 disk radius. Allowing for the uncertainty in disk 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. There is no evidence for any secondary star emission in the He I $\lambda 6678$, He II $\lambda 4686$, or Bowen blend transitions on any of the nights, indicating that the secondary star is exposed to relatively soft ionizing radiation.

The Doppler maps of WZ Sge on August 13 are markedly different from those in the first few days of the outburst. Orbit-resolved spectroscopy on July 28, only 5 days into the outburst, revealed an accretion disk dominated by two spiral arms (Steehgs et al. 2001; Kuulkers et al. 2001) and no sign of any secondary star emission. The first signs of secondary star emission appeared in early August, including August 6. By August 13, not only is the secondary star clearly present in emission, but the accretion flow also has made a major transition. The disk emission is dominated by a strong extended bright spot, very similar to its quiescent structure even though the system

is still 5 mag brighter than its quiescent level. This significant transition in the accretion flow and its implications will be pursued in a future paper discussing additional spectroscopy throughout the 2001 outburst.

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 $493 \text{ km s}^{-1} < K_2 < 585 \text{ km s}^{-1}$, $K_1 < 37 \text{ km s}^{-1}$, and $0.040 < q < 0.075$. In terms of component masses, this corresponds to $0.70 M_\odot < M_1 < 1.4 M_\odot$, while $M_2 < 0.11 M_\odot$.

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