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EMISSION FROM THE SECONDARY STAR IN THE OLD CV WZ SGE

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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 ± 3 km/s and an apparent velocity amplitude of $K_{2_{app}} = 493 \pm 10$ 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 $K_{1_{app}} = 37 \pm 5$ km/s. Accounting for the likely systematic errors affecting both K_1 and K_2 measurements, we conservatively derive $508 < K_2 < 585$ km/s and $K_1 < 37$ 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 conjuction 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 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 overscan 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 normalised 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 occured 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 comparison, $V \sim 8$ at outburst maximum on July 24th (we refer to the AAVSO[1] 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 Hα. 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 zeropoint 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 Hα 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 reflecting 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 profile, 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 outburst 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 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 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.

3.2. *The systemic velocity*

Doppler tomography requires the systemic velocity (γ) 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 Hα line wings. Skidmore et al. (2000) derive a mean systemic velocity of -78 ± 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 motion 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 using the detected S-wave from the secondary star, since its radial velocity is displaced by the true systemic velocity 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 γ is used. We measured the strength of the secondary star emission in each Doppler image, and found that a well defined maximum was achieved for $\gamma = -74 \pm 3$ km/s using the observed Hα emission. The same analysis applied to the Hβ emission also reveals a clear secondary star contribution 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 Hα and Hβ 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 distribution of Hα 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 regularisation (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 $V_x = -140 \pm 10$ km/s, $V_y = 470 \pm 10$ 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_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 Hα emission corresponds to the center of the mass donor we can derive a phase offset of $-17 \pm 1^\circ$ ($\Delta\phi_{spot} = -0.046 \pm 0.003$ in terms of orbital phase) and an apparent radial velocity amplitude of $K_{2_{app}} = 493 \pm 10$ 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 Hβ and $H\gamma$ emission leads to identical phase offsets for both lines (17°) and radial velocities of 478 ± 10 km/s (Hβ) and 479 ± 10 km/s (Hγ) respectively. There is no evidence for any secondary star emission in the HeI6678, HeII4686 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 $K_{2_{app}}$ 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 $K_{2_{app}}$ and K_2 is around 3%. This was derived from Roche geometry calculations across the allowed mass ratio range. Thus our detection of Hα emission at 493 km/s implies $K_2 > 508$ 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 $K_2 < 585$ km/s. Here we have again allowed for a wide range of mass ratios consistent with $M_1 < 1.4 M_\odot$.

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 $K_1 = 48 \pm 6$ km/s from the radial velocities of both Hα 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 $K_{1_{app}} = 40 \pm 10$ km/s, even though the phase offset is still considerable (50°). We applied a similar method to the outburst Hα tomogram, and find a convergence to a center of symmetry at $K_{1_{app}} = 37 \pm 5$ 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°. 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 $K_{1_{app}} = 40 \pm 5$ 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 Hα 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 $0.3M_\odot$ to $1.2M_\odot$. Our lower limit to the radial velocity of the secondary star ($K_2 > 508$ km/s) leads to a mass function of;

$$f(M_1) = \frac{PK_2^3}{2\pi G} = \frac{M_1 \sin i^3}{(1+q)^2} > 0.77 M_\odot$$

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, and a more massive white dwarf is required. With $K_2 > 508$ km/s and $K_1 < 37$ km/s we have $q < 0.073$ implying $M_2 < 0.10 M_\odot$ since $M_1 < 1.4 M_\odot$. 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 $\sim 0.1M_{\odot}$. 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 $M_2 < 0.076M_{\odot}$, 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 ($\Delta\phi_{spot}$) 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 $\Delta\phi_{spot}$ 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 $\Delta\phi_{spot} = 0.046 \pm .003$, and $\Delta\phi_{spot} = 0.041 \pm .003$ 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 Hβ, HeI or HeII (Hα 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 $0.77 < M_1 < 1.4M_{\odot}$, while $M_2 < 0.10M_{\odot}$.

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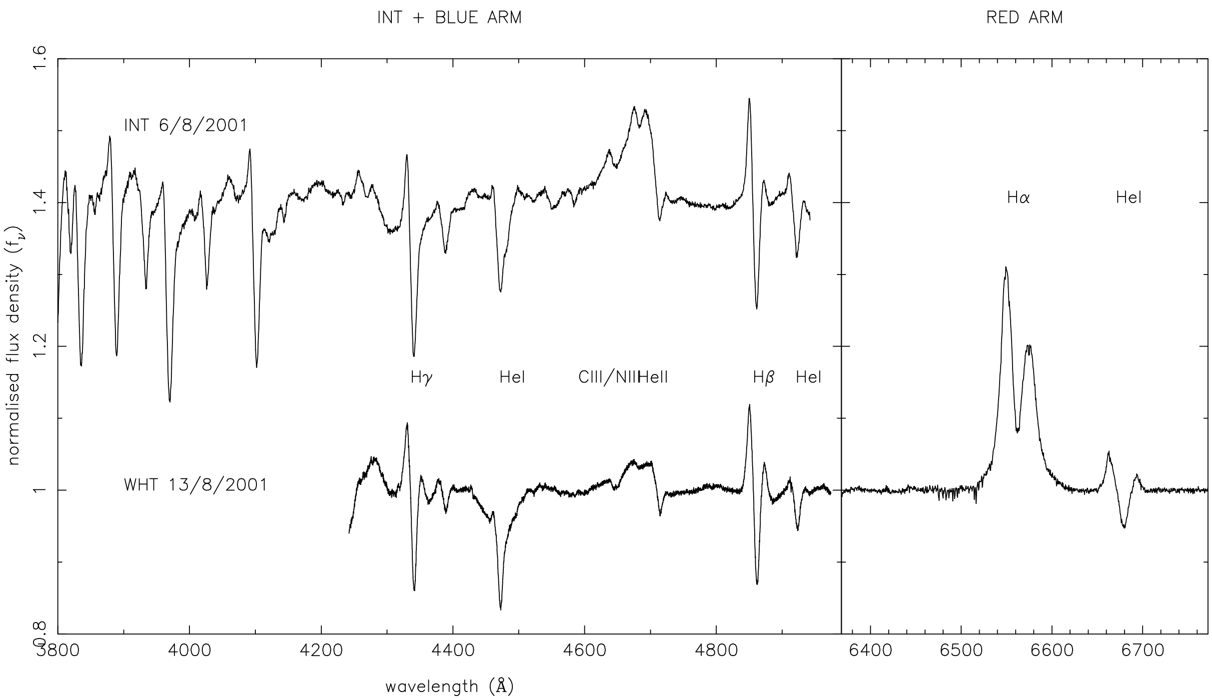

Fig. 1.— The average spectrum of WZ Sge on August the 6th (top) and August the 13th. Spectra are normalised to the continuum and the blue INT spectrum of August the 6th is displaced upwards by 0.4. Several prominent lines are labelled.

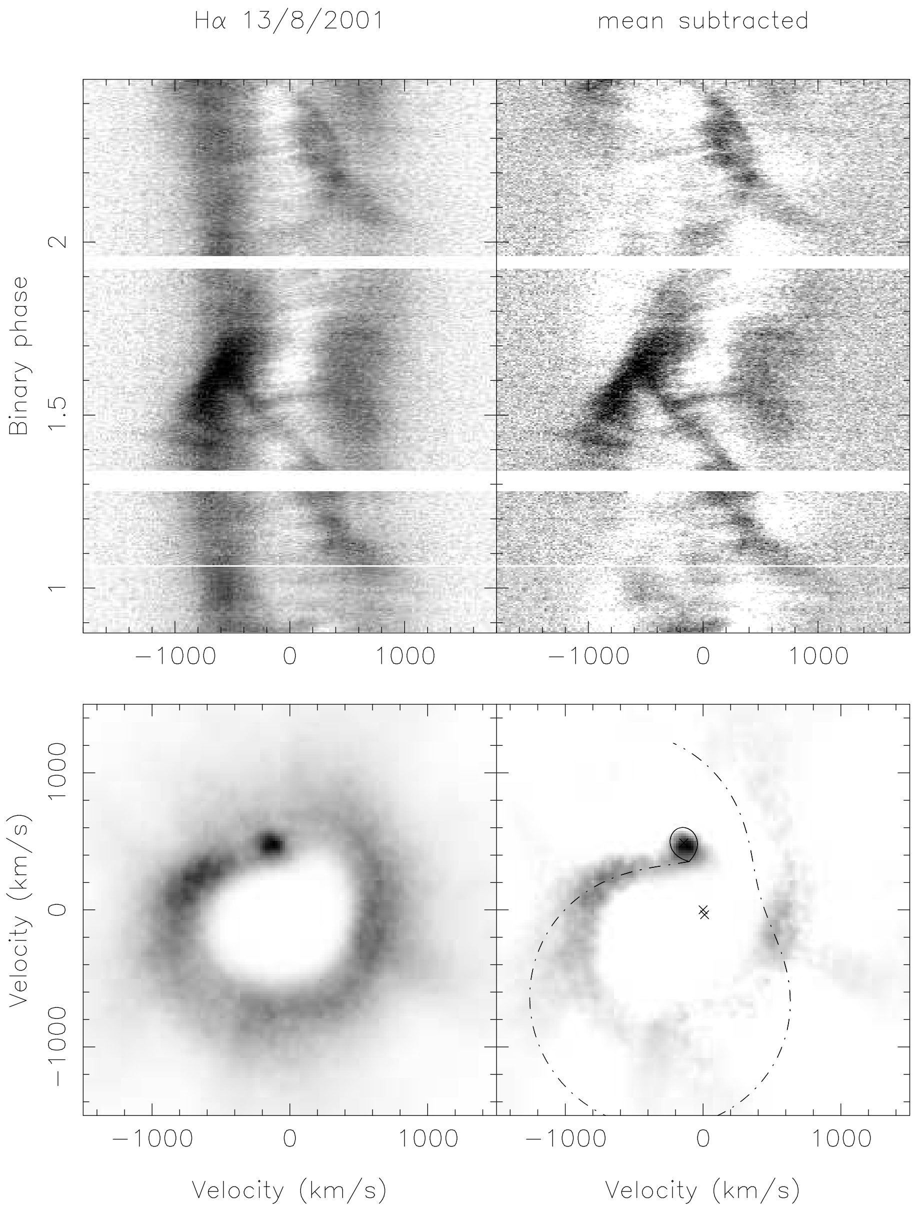

FIG. 2.— Top left: the observed Hα emission as a function of orbital phase on August 13th. Below, the corresponding Doppler map revealing the mass donor star in emission. Top right: the observed data after the mean spectrum was subtracted, highlighting the asymmetries in the accretion flow as well as 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 $\Delta\phi_{spot} = 0.046$.