Investigating the structure of the accretion disc in WZ Sge from multiwaveband time-resolved spectroscopic observations – I

Warren Skidmore,1,2* Elena Mason,2,3 Steve B. Howell,2,3 David R. Ciardi,4 Stuart Littlefair5 and V. S. Dhillon5

1School of Physics and Astronomy, University of St Andrews, North Haugh, St Andrews, Fife KY16 9SS
2Department of Physics and Astronomy, University of Wyoming, PO Box 3905, University Station, Laramie, WY 82071, USA
3Astrophysics Group, Planetary Science Institute, 620 North 6th Avenue, Tucson, AZ 85705, USA
4Department of Astronomy, 211 Bryant Space Science Center, PO Box 112055, University of Florida, Gainesville, FL 32611-2055, USA
5Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH

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ABSTRACT
We present the first of two papers describing an in-depth study of multiwaveband phase-resolved spectroscopy of the unusual dwarf nova WZ Sge. In this paper we present an extensive set of Doppler maps of WZ Sge covering optical and infrared emission lines, and describe a new technique for studying the accretion discs of cataclysmic variables using ratioed Doppler maps. Applying the ratioed Doppler map technique to our WZ Sge data shows that the radial temperature profile of the disc is unlike that predicted for a steady state disc. Time-averaged spectra of the accretion disc line flux (with the bright spot contribution removed) show evidence in the shapes of the line profiles for the presence of shear broadening in a quiescent non-turbulent accretion disc. From the positions of the bright spots in the Doppler maps of different lines, we conclude that the bright spot region is elongated along the ballistic stream, and that the density of the outer disc is low. The velocity of the outer edge of the accretion disc measured from the Hα line is found to be $723 \pm 23$ km s$^{-1}$. Assuming that the accretion disc reaches to the 3:1 tidal resonance radius, we derive a value for the primary star mass of $0.82 M_\odot$. We discuss the implications of our results on the present theories of WZ Sge type dwarf nova outbursts.

Key words: accretion, accretion discs – binaries: close – stars: individual: WZ Sge – novae, cataclysmic variables.

1 INTRODUCTION
Cataclysmic variables (CVs) are interacting binary star systems consisting of a primary white dwarf and a Roche lobe-filling secondary star. Mass exchange occurs via Roche lobe overflow from the secondary star to the white dwarf primary usually via an accretion disc. Dwarf novae are a subclass of CVs in which the mass transfer rate is comparatively low, causing the accretion disc to be unstable. Dwarf novae display semiperiodic outbursts: transferred material is accumulated in the disc until a critical density is reached at which the disc undergoes partial collapse. Understanding the structure and physical processes occurring in the unusual dwarf nova WZ Sge is of vital importance to the understanding of CVs in general. The white dwarf in WZ Sge has been found to have a temperature of $14800$ K (Cheng et al. 1997). WZ Sge’s short orbital period (81.6 min) and low-mass, low-temperature secondary star ($M_2 \sim 0.03 M_\odot$, $T_2 < 1700$ K; Ciardi et al. 1998) suggest that WZ Sge is a very old CV with a degenerate, brown dwarf-like secondary star. WZ Sge was suggested to be the prototype of a subclass of highly evolved CVs with low-mass degenerate hydrogen-rich secondary stars, the WZ Sge systems (Bailey 1979). The outburst properties of WZ Sge (amplitude ~8–9 mag, interoutburst period 33 yr) are amongst the most extreme of all dwarf novae. Several other dwarf novae display extremely large and rare dwarf nova outbursts; these systems were observationally classified as TOA magnetically dwarf novae (Howell, Szkody & Cannizzo 1995). Later work suggested that the TOAD systems may be WZ Sge-type systems (Howell, Rappaport & Politano 1997). Discovering and consolidating the outburst mechanism with the evolutionary state and other properties of WZ Sge (such as the mass transfer rate and the detection of any magnetic field on the primary) will explain many of the poorly understood areas in the study of low mass transfer rate CV systems – principally, the physical processes operating in CV accretion discs.
Analysis of the double-peaked emission lines using Doppler tomography is a well-established method for imaging the accretion discs in CVs (Marsh & Horne 1988). In CV systems with steady state accretion discs, i.e., nova-likes and outbursting dwarf novae, the discs are largely optically thick at most wavelengths and a large percentage of their emitted flux is continuum radiation (Williams 1983; Rutten et al. 1992). Doppler tomography gives only a hint of the underlying structure of optically thick discs, as the large amount of continuum radiation is not imaged by the Doppler tomography process. However, some CV accretion discs may not be optically thick. Observational studies of quiescent dwarf novae indicate that the discs are not in a steady state, have flat temperature profiles (Rutten et al. 1992; Wood, Horne & Vennes 1992) and optically thin regions, i.e., as seen in HT Cas (Vrielmann & Hessman 1998). Optical and infrared photometry of WZ Sge shows a double-humped light curve that is attributed to viewing of the bright spot at all orbital phases (Skidmore 1998). For this to occur, the continuum opacity of the accretion disc in WZ Sge must be very low, i.e., optically thin in the continuum. Thus the line emission from the accretion disc is a powerful tool in determining the characteristics of the disc material. Ratioed Doppler maps can tell us how the physical characteristics of the emitting material varies over velocity space; e.g., by assuming a blackbody source function for the line emission, we can make temperature maps. We expect most parts of the quiescent accretion disc in WZ Sge to be approximately 5000 K, as found for other quiescent dwarf novae (Wood et al. 1992; Vrielmann 1997). The emission-line spectra from accretion discs contain a great deal of information about the temperature, density and velocity gradients within the disc. However, by assuming negligible continuum opacity in the accretion disc and a blackbody source function for the emission lines, we will show that some interesting conclusions can be made about the disc in WZ Sge.

In this paper (Paper I) we present optical and infrared Doppler maps of WZ Sge, develop the idea of ratioed Doppler maps to help investigate the properties of the accretion disc material in CV's, and look at the time-averaged line emission from the disc. In Paper II (Mason et al. 2000) we discuss variations in the phase-resolved spectra of WZ Sge, present a radial velocity study, and show that the measured outer disc velocity of WZ Sge stays constant throughout the quiescent part of the outburst cycle.

## 2 OBSERVATIONS AND DATA REDUCTION

Several sets of data were used in this study see (Table 1). Before analysis, all the individual time-resolved spectra were phased according to the bright spot eclipse ephemeris listed in Table 7 (Skidmore 1998).

### 2.1 The optical spectroscopy

Time-resolved optical spectroscopy of WZ Sge was obtained using ISIS (Carter et al. 1994) on the 4.2-m William Herschel Telescope by Henk Spruit and Rene Rutten. Both arms of ISIS were used with the 5400-Å dichroic, allowing simultaneous observations in two different bands. The R1200B grating and TEKI CCD camera were used on the blue arm; the R1200R grating, GG495 filter and TEK5 CCD camera were used on the red arm. Both CCDs were binned by two in the spatial direction. A total of 376 spectra were obtained in each arm over the two nights (1996 July 27 and 28), these were centred on the Hα and Hβ emission lines. Wavelength dispersion and integration times in both arms were 0.4 Å and 40 s respectively. The seeing was about 1.6 arcsec on both nights and the slit width was 1.2 arcsec. Flux calibration used observations of the standard star Kopff 7 (Baldwin & Stone 1984).

The optical data were reduced using standard IRAF routines. Each frame was bias-subtracted. Flat-fielding introduced more uncertainties than it removed, and was not carried out in the final reduction; however, the sensitivity of the detectors used is known to be very flat. Wavelength calibration in both arms was carried out using Cu-Ar and Cu-Ne arc spectra, which were taken about every 20 minutes. Seven arc lines were fitted in the red arm calibration spectra with either a third-order polynomial or a first-order spline, depending on the position of the arc lines in each arm calibration spectrum. In the blue arm, 35 arc lines were fitted with a first-order spline. The rms errors for the fitting functions are approximately 0.021 and 0.025 Å for the red and blue arms respectively (about a factor of 20 smaller than the dispersion obtainable by the instrumental set-up), giving maximum velocity errors of 2.5 and 5.0 km s⁻¹ respectively. The phased-binned trailed optical spectra are shown in Fig. 1.

### 2.2 The infrared spectroscopy

The observations and reduction of the J- and K-band infrared data are described in Littlefair et al. (2000) and Dhillon et al. (2000) respectively. The J- and K-band time-averaged spectra are shown in Fig. 2. The wavelength-scale calibration errors were 140 km s⁻¹ for the Paβ line (J-band) and 83 km s⁻¹ for the Brγ line (K-band). In the J-band spectrum, the Paβ line (1.28 µm) is free of contamination; however, the Pay line (1.09 µm) is blended with the rapidly varying 1.08-µm Heδ line to such an extent that in our time-resolved data it is not possible to deblend the lines (see fig. 2 in Paper II). In the K-band spectrum the Brγ (2.17 µm), Brδ (1.94 µm) and 2.06-µm Heδ lines are clearly seen. Problems arose when correcting the WZ Sge spectra for telluric absorption in the region around the Brδ line. The Brδ absorption features in the

| Observation date | Wavelength range (Å) | Wave band | Emission lines | Disp. (Å pixel⁻¹) | App. velocity disp., km s⁻¹ | Exposure time (s) | Run length (hr) | No. of orbits |
|------------------|----------------------|-----------|----------------|------------------|-----------------------------|-----------------|----------------|--------------|
| 27/07/96         | 6375–6780            | Optical   | Hα             | 0.40             | 18.1                        | 40              | 5.51           | 4.1          |
| 27/07/96         | 4590–4995            | Optical   | Hβ             | 0.40             | 24.6                        | 40              | 5.03           | 3.7          |
| 28/07/96         | 6375–6780            | Optical   | Hα             | 0.40             | 18.1                        | 40              | 4.07           | 3.0          |
| 28/07/96         | 4590–4995            | Optical   | Hδ             | 0.40             | 24.6                        | 40              | 4.10           | 3.0          |
| 28/07/96         | 18000–24600          | K         | Brγ, Brδ, Heδ  | 13.2             | 193†                       | 480             | 2.70           | 2.0          |
| 08/08/98         | 10300–13400          | J         | Paβ            | 6.22             | 145.6                       | 240             | 6.73           | 3.5          |
Fstar used to flux-calibrate the K-band spectra were badly blended with telluric absorption features (see Fig. 2). Consequently, the Brδ absorption in the flux star spectrum could not be determined before calibrating the WZ Sge data. Any flux measurements derived from the Brδ line should be interpreted cautiously.

3 MASS OF THE WHITE DWARF PRIMARY

The velocity separation of the line peaks was measured by hand from our time-resolved optical data. Spectra in which the bright spot does not affect the position of the peaks were used; the results are listed in Table 2, and further details are given in Paper II. The velocity of the outer edge of the disc is believed to be represented by half the velocity separation of the line peaks (Horne & Marsh 1986). If we assume that the outer edge of the disc is at the 3:1 tidal resonance radius and orbiting with a Keplerian velocity of 723 km s\(^{-1}\), then for an inclination of 75° ± 2° (Smak 1993) and orbital period as listed in Table 7, the corresponding primary mass is \(M_1 = 0.82 \pm 0.10 \, M_\odot\). The size of the 3:1 resonance radius is fixed by \(M_1\) and \(P_{\text{obs}}\), and is effectively independent of \(M_2\) as long as \(M_2 \ll M_1\). The quiescent accretion disc is unlikely to reach

| Table 2 | The measured velocities of the outer edges (half line peak separation) of the accretion disc. |
|---------|-----------------------------------------------------------------------------------------------|
| Line    | Half peak separation \((\text{km s}^{-1})\)                                                     |
| Hα      | 723 ± 23                                                                                     |
| Hβ      | 762 ± 28                                                                                     |

| Table 3 | The measured systemic velocities \((\gamma_0)\) for WZ Sge from different emission lines. |
|---------|---------------------------------------------------------------------------------------------|
| Line    | Rest wavelength \(\AA\) | Systemic velocity \((\gamma_0) \text{ km s}^{-1}\) |
| Hβ      | 4861.33 | \(-84.6 \pm 2.0\) |
| Hα      | 6562.7725 | \(-71.4 \pm 1.9\) |
| Paβ     | 12818.1 | \(10.4 \pm 7.0\) |
| HeI     | 20581.3 | \(144.1 \pm 9.2\) |
| Brγ     | 21655.3 | \(208 \pm 11\) |

Figure 1. The trailed Hβ spectra (left) and Hα spectra (right) of WZ Sge. The data have been binned into 60 phase bins, and are repeated for clarity. The scale on the right of each plot is the flux in mJy.

Figure 2. The time-averaged J-band (left) and K-band (right) infrared spectra. Also shown above the K-band spectrum of WZ Sge is the spectrum of the F star used to flux-calibrate the data. The appearance of absorption features in the F-star spectrum in the region of the Brδ line in WZ Sge is seen.
Figure 3. Doppler maps of the Hβ, Heα, Brγ, Brδ, 2.06-μm Hε1 and Paβ emission lines in WZ Sge, overplotted with the Roche geometry for the system parameters listed in Table 7. The circle represents the 3:1 resonance radius (see Table 2).
beyond the 3:1 resonance radius, as the tidal forces at the 3:1 resonance are strong. Because the mass/radius relation for the secondary star is not uniquely known, and the mass ratio of WZ Sge is so poorly known, we do not attempt to determine the mass of the secondary star. Table 6 in Paper II shows how the accretion disc size is constant throughout the quiescent part of the outburst cycle; one reason for this might be that the outer disc is at the 3:1 tidal resonance radius.

4 DOPPLER TOMOGRAPHY AND THE RATIOED DOPPLER MAP METHOD

To determine a value for the systemic velocity for WZ Sge, radial velocity curves were measured for the Hβ, Hα, Paβ, Brγ and the 2.06-μm He1 line. The measurements for each line were fitted with a sine wave plus a constant offset that represents the systemic velocity. Table 3 lists the measured systemic velocity from each of the emission lines. Further details of the measurement and interpretation of the radial velocity curves are given in Paper II.

We first constructed Doppler maps of each emission line at each of the measured systemic velocities listed in Table 3, a total of 25 maps. No single systemic velocity gave comprehensible results for all five emission lines. Secondly, we considered the velocity resolution and the uncertainties in the wavelength calibration of all five emission lines. Secondly, we considered the velocity resolution and the uncertainties in the wavelength calibration of each data set. The rms errors in the optical wavelength calibrations are 2.5 and 5.0 km s^{-1} for the red and blue arms respectively compared to 140 km s^{-1} and 83 km s^{-1} for J- and K-band data respectively. Also the Brγ, Paβ and 2.06-μm He1 lines show phase-dependent effects due to variations in the strength of the bright spot (see fig. 2 in Paper II). We concluded that the best value for the systemic velocity is the weighted mean of the Hα and Hβ systemic velocities, γ0 = -77.6 ± 9.3 km s^{-1}. This velocity is consistent with previous measurements of the systemic velocity (Gilliland, Kemper & Suntzeff 1986; Spruit & Rutten 1998).

A systemic velocity of -77.6 km s^{-1} was used during construction of the Doppler maps of the Hα and Hβ lines. Due to the large differences between the optical and infrared systemic velocity measurements, the mean of the systemic velocities from the He1 and Brγ lines (166.7 km s^{-1}) was used for the Brγ, Brδ and He1 maps, and 10.4 km s^{-1} was used for the Paβ map.

Prior to calculating the Doppler maps, the continuum background was removed by subtracting off second-order polynomial fits to the continuum parts of the spectra (except for the Brδ line; see below), thus isolating the emission-line flux ready for calculating the Doppler maps. Polynomial fits to the continuum were used in place of a more complicated model as the shape of the continuum was highly variable. The continuum flux outside the double-peaked Brδ line is constant in time. We removed the contamination around the Brδ line in the time-resolved spectra of WZ Sge by subtracting a linear fit to the continuum areas on either side of the double-peaked line. The background-subtracted optical spectra were binned into 60 phase bins, equally spaced around the orbit. The infrared spectra were not phase-binned. Doppler maps were constructed using the Fourier-filtered back projection method (Marsh & Horne 1988; Horne 1991). Fig. 3 shows the Doppler maps for the Hβ, Hα, Brδ, Brγ, Paβ and 2.06-μm He1 lines. Overplotted is the Roche geometry for WZ Sge with the parameters listed in Table 7.

To highlight regions of excess Hα emission (possibly optically thin emission), we divided the Hα background-subtracted trailed

Table 4. Intensity ratios for the hydrogen lines for a variety of temperatures and assuming a blackbody (i.e., saturated) source function (these ratios are calculated for fluxes in mJy).

| Temp     | Hα/Hβ | Brγ/Brδ |
|----------|-------|---------|
| 4000 K   | 2.779 | 0.910   |
| 5000 K   | 1.905 | 0.885   |
| 7500 K   | 1.172 | 0.855   |
| 10 000 K | 0.935 | 0.841   |

Figure 4. The differenced trailed spectrogram used to make the residual Doppler map. The lack of an apparent hot spot in the trailed spectrum shows that the hot spot line emission is hot and/or optically thick.

Figure 5. Doppler map highlighting the areas of excess Hα emission (see text for method).
spectrum (right-hand panel of Fig. 1) by 1.905, and the Hβ trailed spectrum (left-hand panel of Fig. 1) was subtracted in velocity space leaving a residual trailed spectrum (Fig. 4). From the residual trailed spectrum we constructed the Doppler map shown in Fig. 5. The significant Hα excess in the disc indicates optically thin line emission, as we expect the disc temperature to be about 5000 K. The residual map is effectively identical to the map created by subtracting the Hβ map from the Hα map (with the appropriate factors included; see equation 1 and Table 4). Throughout this paper all theoretical flux ratios will assume simple blackbody source functions; this is because for some emission lines analysed here, there are no published ratios derived from physical disc models. However, where these ratios are available (e.g. Williams & Shipman 1988; Randich et al. 1991), they are found not to depart substantially from the simple blackbody case.

4.1 The ratioed Doppler map method

Several factors affect the scaling of a Doppler map constructed using Fourier-filtered back projection:

(i) The integrated flux at a point in the map depends on the number of spectra used during construction of the map.
(ii) Fourier-filtering the data before constructing the Doppler map alters the final fluxes in the map.
(iii) Data can be affected by slit losses, and corrections are possible only during data reduction.

For Doppler maps of two lines constructed from the same number of spectra with the same Fourier filtering and the same slit losses, the flux scaling for each map will be the same. We can simply divide one map by the other. In our data there are no flux scaling problems in the ratioed maps constructed from the Hα and Hβ, and Brγ and Brδ maps.

It is possible to recalibrate Doppler maps calculated from dissimilar data sets. This is done by comparing a synthesized time-averaged spectrum calculated from the Doppler map with the time-averaged spectrum of the background-subtracted spectra. However, problems arise due to the differences in the seeing when different data sets are gathered, systematic changes in the state of the target between observations, and differences in the Doppler tomography process applied to each data set. In this paper we concentrate on our simultaneous data sets.

Ratioed Doppler maps for WZ Sge are shown in Fig. 6. Areas in the ratio maps corresponding to areas of positive flux in the original maps are seen as smoothly varying grey areas. Edges or discontinuities, i.e., an abrupt change from white to black, arise at positions where the flux in the dividing map is small and changes from positive to negative. Discontinuities arise at high velocities due to low S/N, and at lower velocities due to features arising in the dividing map.

The measured flux ratio, R, of two emission lines at a particular point in a ratioed Doppler map is not necessarily the true flux ratio, Fα/Fβ. If the time-resolved spectra of the two lines under consideration consist of only a sinusoidal velocity component, i.e., a bright spot, then the ratio of the sinusoidally varying component in the ratioed Doppler map Rspot is simply the ratio of the emission-line fluxes Fα spot/Fβ spot. If, however, components in the two line profiles have constant velocities, i.e., the disc emission, the measured flux ratio in the ratio map Rdisc is related to the real flux ratio Fα disc/Fβ disc according to

\[ R_{\text{disc}} = \left( \frac{F_{\alpha \text{ disc}}}{F_{\beta \text{ disc}}} \right) \times \frac{\lambda_\beta}{\lambda_\alpha} \] (1)

where λα and λβ are the rest wavelengths of the lines being studied. In reality, the bright spot emission is superimposed over the disc emission. Separating the disc and bright spot fluxes from the Doppler maps is not possible; thus any flux ratios in the
hotspot region are only a rough guide to the true flux ratio. In this paper we do not try to interpret the flux ratio measured at the bright spot position.

We experimented with Doppler maps constructed using background-subtracted trailed spectrograms ratioed in velocity space; this resulted in the presence of many high points or flares in low S/N areas of every ratioed spectrum. Marsh & Horne (1988) demonstrate the effects of high points or flares in individual phase-resolved spectra: a single flare produces a streak across the map corresponding to the phase and velocity of the flare. Thus, maps produced from ratioed trailed spectrograms were rendered useless by the large number of streaks across them.

5 RADIAL PROFILES OF LINE FLUX, LINE RATIOS AND DISC TEMPERATURE

Using our Doppler maps and ratioed Doppler maps, we constructed radial profiles by calculating the median of the azimuthal flux or line ratio at each radius in velocity space centred on zero velocity. For the system parameters listed in Table 7 the position of the white dwarf in velocity space is so close to zero velocity that the difference is negligible. Segments of the Doppler maps that showed effects of the bright spot were excluded when calculating the median profile (see Table 5). The radial profiles are therefore an average for the normal areas of the accretion disc. The conversion to real-space profiles assumed that velocities were due to Keplerian motion around a 0.82-M\(_{\odot}\) primary (Table 7). The radial flux and ratio profiles are shown in Figs 7 and 8. Using the H\(_{\alpha}/H\beta\) and Br\(_{y}/Br\delta\) ratio profiles, we calculated radial temperature profiles assuming a blackbody source function for the line emission.

6 TIME-AVERAGED ACCRETION DISC EMISSION-LINE SPECTRA

To calculate the time-averaged emission-line flux from the accretion disc, we masked out the bright spot emission from the trailed spectrogram of a particular emission line, averaged the remaining flux, and removed the flux from a 15 000-K solar composition white dwarf model (Cheng et al. 1997 find the white dwarf temperature to be 14 800 K) plus a constant offset to remove
any remaining continuum flux. The disc emission spectra for the four uncontaminated hydrogen lines and the 2.06-μm He I line are shown in Figs 9 and 10. The disc emission spectra were fitted with a double-Gaussian model, and the results of these fits are listed in Table 6. The V-shaped central troughs in the Hα, Hβ and Brγ disc spectra indicate the effects of high shear broadening within the disc (Horne & Marsh 1986; Horne 1995).

7 INTERPRETATION

7.1 The individual and residual Doppler maps

All of our Doppler maps (Fig. 3) show a clear bright spot region and asymmetric disc emission. The Hα map is similar to the 1995 July Hα Doppler map presented by Spruit & Rutten (1998). The Brγ Doppler map is badly affected by artefacts, because telluric features could not be properly removed from the time-resolved spectra during the original reduction (see Section 2.2). An optically thick or high-temperature region near the bright spot position is clearly shown in the map of residuals in Fig. 5. Fig. 11 shows the positions of peak line emission in the Doppler maps presented in this paper, and the points appear to be orientated along the accretion stream and not concentrated around one point; this suggests that the stream flows almost unaffected through the outer disc regions, and that the bright spot is actually an extended region of emission aligned along the stream. For the stream material to be unaffected by the disc material, the accretion disc must have a very low density. A low-density disc is consistent with the idea of a disc with low continuum opacity, as needed to explain the double-humped photometric light curves.

Because the bright spot in a CV does not lie on the line of centres of the system, the bright spot photometric eclipse ephemeris used to phase our WZ Sge data is offset from true binary phase zero by a small, but unknown, amount. Using the system parameters listed in Table 7, and assuming that the bright spot emission lies along the ballistic trajectory, we found that a phase offset of $-0.022 \pm 0.004$ from the bright spot photometric ephemeris predicted a ballistic stream path that was close to all measured positions of peak bright spot flux in Fig. 11; this compares to a phase offset of $-0.041 \pm 0.003$ estimated by Spruit & Rutten (1998). Paper II discusses the dependence of phase offset with orbital period, and provides further evidence that the bright spot emission lines in WZ Sge originate from material following the ballistic trajectory.

7.2 Ratioed Doppler maps, radial profiles and time-averaged disc spectra

Ratio maps of the simultaneously observed hydrogen lines in our data are shown in Fig. 6. If we assume the following:

1) blackbody source functions for the emission lines;
2) negligible continuum opacity in the disc;
3) negligible coronal material above the disc, and
4) a disc temperature of 5000 K,
then the majority of the disc line emission in WZ Sge is apparently optically thin. There is an obvious change in the flux ratio in the disc/stream interaction region, indicating that the bright spot is hot.

In Figs 7 and 8 the radial flux profiles do not follow the simple emission law predicted for an α disc in which the fluxes are predicted to rise smoothly toward the centre of the disc. In areas of the disc close to the white dwarf primary, the line flux drops but the ratio of the Hα/Hβ and Brγ/Brδ line emission decreases; therefore the apparent optical depth and/or the temperature increases. The line ratios in the inner disc region suggest that the inner disc may be a strong continuum emitter. The temperature profile derived from the Hα/Hβ ratios is very flat, and the temperatures seen are lower than the expected 5000 K, being only 3000±4000 K. The ratios in the Brγ/Brδ flux ratio profile are largely beyond those predicted for an infinite-temperature black-body source function. The Brγ and Brδ Doppler maps were constructed from lower quality data than the Hα and Hβ maps; thus we have lower confidence in the flux and ratio profiles.

8 DISCUSSION OF THE DISC STRUCTURE AND THEORIES EXPLAINING THE OUTBURST PROPERTIES OF WZ SGE

The structure of the accretion disc in WZ Sge – I

Table 6. Results of fitting the time-averaged disc emission spectra (see Figs 9 and 10) with a double Gaussian.

| Line    | Wavelength of peaks | FWHM     | Amplitude mJy |
|---------|---------------------|----------|--------------|
| Hβ      | 4849.15 ± 0.02 Å    | 13.27 ± 0.05 Å | 0.870 ± 0.003 |
|         | 4870.92 ± 0.02 Å    | 12.80 ± 0.05 Å | 0.817 ± 0.003 |
| Hα      | 6547.98 ± 0.01 Å    | 17.55 ± 0.03 Å | 3.106 ± 0.005 |
|         | 6575.36 ± 0.01 Å    | 17.68 ± 0.03 Å | 2.978 ± 0.004 |
| Paβ     | 12787 ± 2 Å         | 50 ± 3 Å   | 0.87 ± 0.04   |
|         | 12847 ± 2 Å         | 52 ± 3 Å   | 0.96 ± 0.04   |
| Brγ     | 21620 ± 1 Å         | 65 ± 2 Å   | 0.89 ± 0.02   |
|         | 21714 ± 1 Å         | 71 ± 2 Å   | 0.80 ± 0.02   |
| HeI     | 20545 ± 5 Å         | 85 ± 8 Å   | 0.43 ± 0.03   |
|         | 20638 ± 4 Å         | 75 ± 7 Å   | 0.39 ± 0.03   |

Figure 10. The time-averaged HeI (top), Paβ (middle) and Brγ (bottom) accretion disc spectra.

Figure 11. The points of maximum emission and the point of high optical depth (labeled Diff) in the residual map. Note how the points appear aligned along the stream rather than grouped around one bright spot position.
systems; most of these are based on outburst theories have been developed specifically for the WZ Sge every several hundred to several thousand days. Several successful characteristics: some systems have low-amplitude outbursts ($\Delta M \sim 2$ mag) every few tens of days, while the WZ Sge or TOAD systems have high-amplitude outbursts ($\Delta M \gtrsim 6$ mag) every several hundred to several thousand days. Several successful outburst theories have been developed specifically for the WZ Sge systems; most of these are based on $\alpha$ disc models that use a very low viscosity parameter $\alpha_{\text{cold}}$ during quiescence ($\alpha_{\text{cold}} = 0.003$ in WZ Sge compared to $\alpha_{\text{cold}} = 0.03$ in other systems) (Osaki 1995). Physical justification for an extremely low value of $\alpha_{\text{cold}}$ is unclear. A physical mechanism giving a small value for $\alpha_{\text{cold}}$ is suggested by Meyer & Meyer-Hofmeister (1999), in which the viscosity in the quiescent accretion disc is due to the magnetic field of the secondary star. The magnetic field of the secondary will be greatly reduced when the secondary star becomes degenerate; this is consistent with the idea that WZ Sge-type systems or TOADs are post-period-minimum systems with degenerate secondary stars (Howell et al. 1997). If weak magnetic fields are present within the disc, the disc may be unstable and become turbulent (Balbus & Hawley 1991; Horne 1995). Figs 9 and 10 are consistent with the emission from a non-turbulent accretion disc showing shear broadening. Turbulence within accretion discs is an efficient source of viscosity. The lack of turbulence in the accretion disc in WZ Sge could explain the extremely low quiescent disc viscosity, and may be due to the presence of a non-magnetic degenerate secondary star.

The highest density regions in a disc with low $\alpha$ and low mass transfer rate will be in the inner disc. The photometric model of WZ Sge described in Ciardi et al. (1998) suggests that there is an uneclipsed source of continuum flux arising from the accretion material. The uneclipsed continuum source could be the optically thick inner region of the accretion disc suggested by the $H\alpha/H\beta$ ratio radial profile.

A hypothetical $\alpha$ disc has a simple temperature profile, $T \propto r^{-3}$. Thus emission rises smoothly toward the centre, and is constant around a circumference of a particular radius. The accretion disc in WZ Sge is asymmetric and has radial flux and temperature profiles that are unlike those predicted by $\alpha$ disc models.

## 9 CONCLUSIONS

An extensive set of Doppler maps of WZ Sge is presented. The accretion disc is found to be asymmetric, and the bright spot region is shown to be extended along the mass transfer stream. We conclude that the outer layers of the accretion disc must be of low density in order to allow the stream to penetrate the disc and continue following the ballistic trajectory. A low-density outer disc is consistent with the idea of a disc with low continuum opacity, as needed to explain the double-humped photometric light curves. The idea of ratioed Doppler maps is presented. Using the new ratioed Doppler map method and by constructing radial profiles of the accretion disc line flux ratios, we have shown that the accretion disc in WZ Sge has a flat temperature profile, unlike that predicted for a steady state $\alpha$ disc. Time-averaged disc emission-line spectra are presented that show evidence for shear broadening in a non-turbulent quiescent accretion disc. We measure the velocity of the outer edge of the accretion disc in WZ Sge to be approximately $723 \, \text{km} \, \text{s}^{-1}$. By assuming that the accretion disc reaches to the 3:1 tidal radius, we estimate a primary mass of approximately $0.82 \, M_\odot$ (support for this assumption comes from the fact that the velocity of the peaks in the optical emission lines does significantly vary during quiescence—see Paper II). The present outburst theories for WZ Sge-type systems are discussed and some problems highlighted; i.e., outburst theories use $\alpha$ discs, but the disc structure and radial profiles seen in WZ Sge are not like those predicted by simple disc models. We suggest that the non-turbulent disc in WZ Sge is consistent with the evolutionary status of the object, i.e., that the secondary star is degenerate and non-magnetic, and that the lack of magnetically induced turbulence within the disc justifies the idea of a very low-viscosity quiescent accretion disc. Application of the ratio map method to WZ Sge-like systems will provide the best observational basis on which to base physically realistic accretion disc models.

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**Table 7.** System parameters used or determined in this analysis. Fig. 12 shows the real space geometry of a system with these parameters.

| Parameter | Value | Reference |
|-----------|-------|-----------|
| $P_{\text{orb}}$ | $0.05668784707 \, \text{days}$ | 1. |
| $T_0$ | $2437547.728868 \, \text{BJJD}$ | 1. |
| $\gamma_0$ | $-77.6 \pm 9.3 \, \text{km} \, \text{s}^{-1}$ | 2. |
| $\phi_r$ | $-0.022 \pm 0.004$ | 2. |
| $R_{\text{disc}}$ | $1.94 \pm 0.14 \times 10^{10} \, \text{cm}$ | 2. | ($R_{3:1}$ for $H\alpha$) |
| $M_1$ | $0.82 \pm 0.10 \, M_\odot$ | 2. |
| $M_2$ | $0.058 \, M_\odot$ | 3. |
| $i$ | $75^\circ$ | 3. |

1. Skidmore (1998), 2. this paper, 3. Smak (1993).

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**Figure 12.** The system geometry of WZ Sge in real space, calculated using the system parameters listed in Table 7. Units are in metres. Zero in the y direction corresponds to photometric phase zero. The horizontal line represents the Earth–Moon distance, and the circle represents the size of Jupiter.
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REFERENCES

Bailey J., 1979, MNRAS, 189, 41
Balbus S., Hawley J., 1991, ApJ, 376, 214
Baldwin J., Stone R., 1984, MNRAS, 206, 241
Carter D. et al., 1994, http://www.ing.iac.es/~manuals/html_manuals/wht_instr/isis_hyper/isis_hyper.html
Cheng F., Sion E., Szkody P., Huang M., 1997, ApJ, 484, 149
Ciardi D., Howell S., Hauschildt P., Allard F., 1998, ApJ, 504, 450
Dhillon V. et al., 2000, MNRAS, 314, 826
Gilliland R., Kemper E., Suntzeff N., 1986, ApJ, 301, 252
Horne K., 1991, in Shafter A. W., ed., Proc. 12th North American workshop on CVs and LMXBs, Mount Laguna Obs. Publ., San Diego
Horne K., 1995, A&A, 297, 273
Horner K., Marsh T., 1986, MNRAS, 218, 761
Howell S., Szkody P., Cannizzo J., 1995, ApJ, 439, 337
Howell S., Rappaport S.,Politano M., 1997, MNRAS, 287, 929
Littlefair S., Dhillon V., Howell S., Ciardi D., 2000, MNRAS, 313, 117
Marsh T., Horne K., 1988, MNRAS, 235, 269
Mason E., Skidmore W., Howell S., Ciardi D., Littlefair S., Dhillon V., 2000, MNRAS, 318, 440 (Paper II, this issue)
Meyer F., Meyer-Hofmeister E., 1999, A&A, 341, 23
Osaki Y., 1995, PASJ, 47, 47
Randich M., Giovannardi C., Natta A., Palla F., 1991, A&AS, 88, 31
Rutten R., Kuulkers E., Vogt N., van Paradijs J., 1992, A&A, 265, 159
Skidmore W., 1998, PhD thesis, Univ. Keele
Smak J., 1993, Acta Astron., 43, 212
Spruit H., Rutten R., 1998, MNRAS, 299, 768
Vrielmann S., 1997, PhD thesis, Univ. Göttingen
Vrielmann S., Hessman F., 1998, ASP Conf. Ser. 137, Wild Stars in the Old West. Astron. Soc. Pac., San Francisco, p. 410
Williams G., 1983, ApJS, 53, 523
Williams G., Shipman H., 1988, ApJ, 326, 738
Wood J., Horne K., Vennes S., 1992, ApJ, 385, 294

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