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Research Note

Time-resolved infrared spectroscopy of WZ Sge during superoutburst: Evidence for spiral waves in the accretion disc

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Abstract. Time-resolved *J* and *K* band spectra were obtained for WZ Sge four days into its 2001 superoutburst. These data represent the first time-resolved IR spectra obtained of any dwarf nova during a superoutburst. The spectra show the usual broad emission lines due to H and He I plus strong He II (1.163 μm), the latter line being essentially absent at minimum light. The *J*-band spectra contain complex line emission from C I, Fe I, Na I, and Ca I and show asymmetric H and He line emission from the accretion disc. The *K*-band continuum reveals an increasing slope to the red as seen during minimum light. Doppler maps produced from the IR spectra indicate the presence of asymmetric emission within the accretion flow, in agreement with the optical detection of prominent spiral arms present within the accretion disc.

Key words. stars: cataclysmic variables – stars: individual: WZ Sge – accretion, accretion disks

1. Introduction

WZ Sge has been considered the quintessential Tremendous Outburst Amplitude Dwarf nova (TOAD; See Howell et al. 1995a) having an orbital period of 81.6 min, rare superoutbursts (which until now occurred on 33 year cycles), and probably a brown dwarf-like secondary star of mass near 0.05 $M_\odot$ (Steeghs et al. 2001; Ciardi et al. 1998). On 23 July 2001, WZ Sge began a superoutburst only 23 years after its previous one, 11 years earlier than predicted. Initial multi-wavelength observational work has been summarized in Kuulkers et al. (2002), Steeghs et al. (2001) present optical spectroscopy focusing on emission lines from the irradiated secondary, and Patterson et al. (2002) present the results from their optical photometric campaign.

Optical photometry and spectroscopy of WZ Sge during the superoutburst indicate that the asymmetric features in the accretion disc (spiral waves) are present during the early outburst. After day 12 however, superhumps began to develop and the large optical light curve modulations as well as the accretion disc asymmetries (arms) died away.

We report here on the first detailed IR spectral observations ever obtained for any superoutbursting dwarf nova. These data provide evidence for an IR detection of spiral waves in the accretion disc. Details of these and our additional fall 2001 IR spectroscopic observations will be presented in a future paper.

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2. Observations

Time-resolved *J* and *K* band spectra of WZ Sge were obtained on 2001 July 27 12.0 to 14.3 hr (UT) at UKIRT using the cooled grating spectrograph (CGS4). The infrared observations covered the wavelength range from 1.0 to 1.35 and 1.85 to 2.47 microns with the spectral regions short-ward of ~1.9 microns in *K* being unusable due to the presence of strong telluric absorption. The night was photometric throughout with ~0.6 arcsec seeing. We used the 40 l/mm grating and a slit width of 2 pixels (1.2 arcsec). The spectra were reduced in the normal manner, that is, linearization and bias and flat field correction, wavelength calibration using an argon arc lamp, bad pixel removal, and telluric band removal using A star observations near in time and position (after patching hydrogen lines out of their spectra) were applied. Each spectrum was optimally extracted (including removal of any optical curvature) and flux calibrated using observations of the stars BS 7724 (*K*) and BS 7546 (*J*) whose spectra were obtained in the middle of each time-series and which had a similar airmass. The use of limited standards produced fluxes good to ~20% with regions of telluric water being slightly worse.

Nearly one complete binary orbit was covered in each bandpass with an effective integration time for each spectrum of 3.6 min resulting in a total of 15 *J* band and 12 *K* band spectra. Figure 1 shows our time-resolved spectra for WZ Sge in both *J* and *K* and Table 1 presents the observing log. The orbital phasing used here and throughout this paper is the orbital

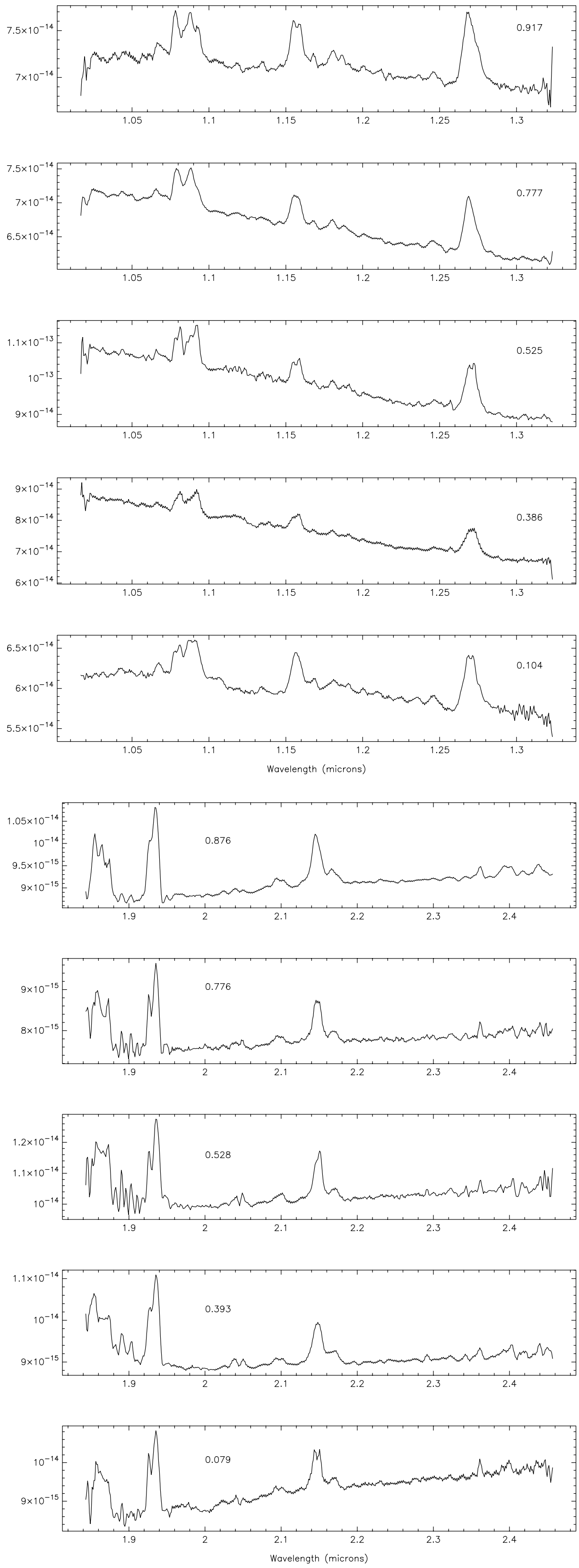

Fig. 1. Sample *J* and *K* spectra covering one binary orbit. The strong H and He emission lines are obvious as well as a number of weaker, but real metal emission lines. Note that the strong emission lines are generally double-peaked and that the *K* continuum has a red-ward slope to it. A few of the spectra show a high frequency pattern, a left over effect caused by our best effort de-ripple to the under-sampled data. The flux is in units of W m^{-2} μm^{-1}.

Table 1. WZ Sge observing log – 27 July 2001 UT.

J-Band Phase	Time[a]	K-Band Phase	Time[a]
0.020	0.09524	0.034	0.03937
0.066	0.09786	0.083	0.04220
0.112	0.10049	0.133	0.04504
0.160	0.10320	0.448	0.00620
0.441	0.06245	0.584	0.01387
0.488	0.06507	0.632	0.01662
0.535	0.06774	0.682	0.01945
0.581	0.07036	0.732	0.02229
0.628	0.07303	0.782	0.02512
0.740	0.07936	0.831	0.02791
0.785	0.08199	0.881	0.03075
0.834	0.08465	0.931	0.03358
0.880	0.08732		
0.926	0.08995		
0.973	0.09257		

[a] Mid-exposure HJD 2452118+.

ephemeris and period given in Table 7 of Skidmore et al. (2000). A number of emission lines are seen in these spectra and we considered spectral lines real if they appeared in a majority of the time-resolved observations, particularly those covering phases 0.4–0.8. Emission lines from H and He are easily identified and we also see weaker, often variable and blended emission lines from Fe I (1.044 1.15, 1.168, 1.181, 1.21 μm), Na I (1.049, 1.12, 1.14, 2.34 μm), Ca I (1.31/1.33, 2.25? μm), and C I (1.168, 1.181, 1.188 μm). The identification of carbon emission is particularly interesting to note as WZ Sge has been shown to contain a white dwarf which is 5 times over abundant in carbon (Cheng et al. 1997) compared with solar. In the early stages (first week or so) of a superoutburst, TOADs such as WZ Sge are known to produce quite strong winds which eject material with velocities greater then the escape velocity of the binary (Howell et al. 1995b). Therefore, the carbon emission may be evidence of atmospheric ejection from the white dwarf itself.

Convolving numeric filters with the average J and K WZ Sge spectra resulted in mean J and K magnitudes of 11.6 ± 0.8 and 11.55 ± 0.8 respectively on this night with a V magnitude of ~9.2 reported by AAVSO observations. Thus, the fluxes at V and J are similar (~7.9×10^{-14} W m^{-2} μm^{-1}) while that at K is lower, being near 1×10^{-14} W m^{-2} μm^{-1}.

3. Results and discussion

Examination of the fluxes of the IR spectra (Fig. 1) show that the J band spectra are highly modulated on the orbital period. Using three line free continuum regions (±0.1 microns) in our spectra (1.05, 1.22, and 2.25 μm) we find that the J band continuum light curves clearly show a strong flux increase centered near ϕ = 0.6 and equal to ~0.5 mags. The duration of this flux increase and its orbital phase location, while tempting to assign to the irradiated face of the secondary star, are too long in time and too asymmetric in shape to be consistent with their source being an irradiated secondary star. The K band continuum is modulated in a similar fashion but of lower amplitude (~0.15 mag). These results are consistent with the optical light curve structure seen by Patterson et al. (2002) during the first weeks of the superoutburst.

Measurement of the equivalent widths for the three strongest H and He lines in each band show that they follow the continuum modulation with respect to orbital phase, that is, the equivalent widths increase during the 0.5–0.6 phase interval. This implies that a larger velocity spread of material (within the accretion disc) contributes to the line flux at these phases. However, measurements made for the three C I emission lines reveal essentially constant fluxes and equivalent widths throughout the orbit.

We employed Doppler tomography techniques to map the line emission distribution of the strong lines in the corotating frame of the binary (see Marsh 2001 for a review). Our velocity resolution in these data is ~35 km s^{-1}. While the Paβ and He II line are suitably isolated, Paγ was blended with the strong He I line at 1.083. Those two blended lines were thus fitted simultaneously using a separate image for each line. The four derived Doppler tomograms are presented as grayscales in Fig. 2. The velocity extent of the He I image appears larger than the others but given the moderate S/N we can not be sure this is real.

The disc emission is not well resolved in the Paschen lines, with both Paβ and Paγ tomograms sharing the same emission morphology. It appears that the right hand side of the disc is much more dominant in these lines, a feature also shared to a lesser extent by the He I emission. This strong asymmetry in the Paschen emission lines reflects the large radial velocity modulations that were obtained for these lines, in clear contrast to He II. To see the differences, compare these maps with those presented by Mason et al. (2000) for WZ Sge during minimum light.

Doppler tomography of the optical He II line at 4686 Å produced using data obtained one day after ours, revealed an accretion disc dominated by two prominent spiral arms (Kuulkers et al. 2002). Given the lower spectral resolution of our IR data, our He II tomogram at 1.163 μm shares the same disc asymmetry and approximate velocity structure, indicating that the spiral arms are identified in the IR. The spiral arm structures are likely to be the cause of the highly modulated nature of WZ Sge's light curve observed during the first 10 days of its superoutburst.

The tomograms provide us with a qualitative picture of the line emission regions. The prominent spirals that are visible in the optical appear to affect the IR disc emission in very much the same way in both the continuum and in the emission lines. Our results provide the first detection of an accretion disc spiral wave in the infrared.

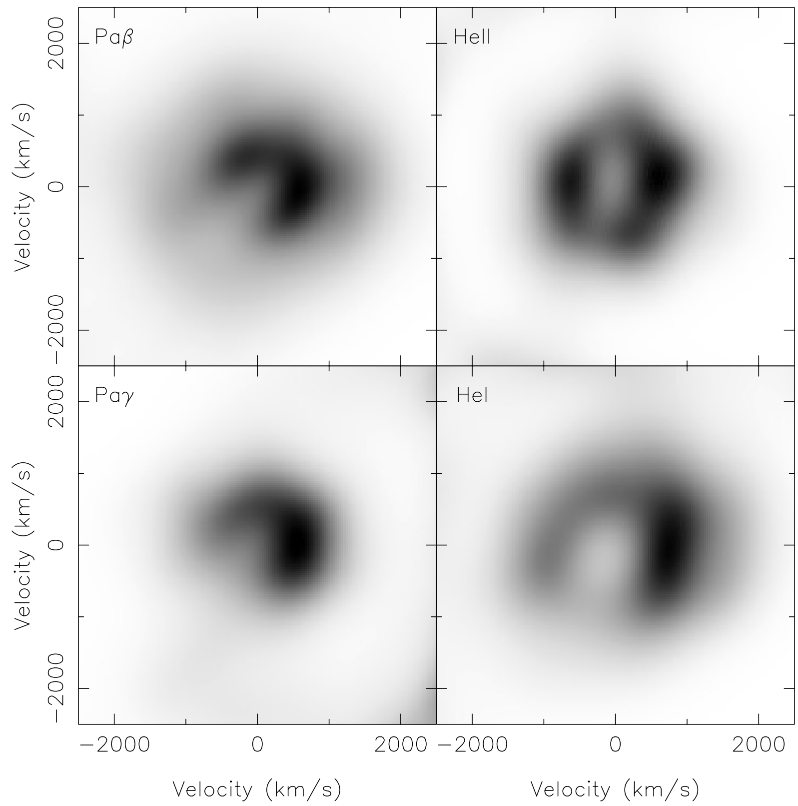

Fig. 2. IR Doppler maps of WZ Sge produced from spectra obtained on day four of the 2001 superoutburst. Note the two symmetric arc-shaped regions in the He II map, consistent with the presence of spiral arms in the accretion disc. The Paschen emission lines show a strong asymmetric distribution.

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