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KECK INFRARED SPECTROSCOPY OF WZ SAGITTAE: DETECTION OF MOLECULAR EMISSION FROM THE ACCRETION DISK

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ABSTRACT

Time-resolved IR spectroscopy of WZ Sge was obtained using NIRSPEC on Keck II. We detect CO and H_2 emission from the accretion disk, placing WZ Sge in a rarefied class of astronomical objects including young stellar objects and high-luminosity early-type stars. During the eclipse phase, the molecular emission greatly weakens, but no firm evidence for the secondary star is seen, allowing new limits on its luminosity to be determined. The detection of molecular emission provides physical properties $T = 3000$ K and $n_{\rm H} > 10^{10}$ cm^{-3} within the outer disk. Such a cool, dense region not associated with areas of H I and He I emission provides the first observational confirmation of predictions made by accretion disk models.

Subject headings: accretion, accretion disks — molecular processes — stars: dwarf novae — stars: individual (WZ Sagittae)

1. INTRODUCTION

Infrared spectroscopy has been shown to be a powerful tool for the study of cataclysmic variables (CVs) and has opened new research avenues for our understanding of the mass-losing secondary stars. Results to date have revealed that these secondaries can have odd abundances, be of very low mass, and have very cool temperatures.

WZ Sge is a very famous, bright variable star now known to be the closest cataclysmic variable (at a distance of 43.5 ± 0.3 pc; Harrison et al. 2004a). It is also the flagship tremendous outburst amplitude dwarf (TOAD) novae, highly evolved binary systems having, among other properties, superoutbursts of 6 mag or more, and containing very low mass, brown dwarf–like secondary stars (Howell & Skidmore 2000). WZ Sge has been observed a number of times in the IR, including a detailed time-resolved spectroscopic study (Skidmore et al. 2000; Mason et al. 2000). However, until now its secondary star has not shown itself directly, thereby allowing some latitude in speculation as to its true nature.

Steeghs et al. (2001) observed narrow emission lines due to irradiation of the secondary during superoutburst and found a mass ratio of $0.040 < q < 0.075$. Patterson et al. (2002) derive a white dwarf mass of $M_1 = 1.0 \pm 0.2\ M_\odot$, indicating that the secondary star in WZ Sge has a mass similar to those of brown dwarfs with $M_2 \sim 0.07\ M_\odot$. Ciardi et al. (1998) used IR photometry and spectroscopy to set limits as well, which are in general agreement, albeit a bit lower ($\sim 0.05\ M_\odot$).

WZ Sge has the longest known interoutburst interval of any dwarf nova. Two leading theories to explain this behavior invoke either a very low viscosity parameter ($\alpha = 0.001$; Smak 1993; Osaki 1996) or a truncated inner disk (Hameury et al. 1997). The latter model invokes evaporation or a magnetosphere to truncate the inner disk, keeping it stable against outbursts. In this configuration, the disk of WZ Sge during quiescence should closely resemble the disks of SU UMa systems, because the viscosity has a normal value ($\alpha = 0.1$). If the low-α model is correct, the accretion disks of WZ Sge–type systems are somehow different from the other SU UMa systems.

We have used NIRSPEC on Keck II to obtain the highest signal-to-noise ratio (S/N), moderate-resolution *K*-band spectrum ever obtained for WZ Sge. We find that there is no direct evidence in this spectrum for the detection of the secondary star, and thus we derive new limits on its luminosity. The most remarkable aspect of these new spectra is the detection of CO and H_2 in emission arising from the accretion disk. This latter discovery allows us to provide good estimates for the temperature and density values in this previously invisible outer accretion disk region.

2. OBSERVATIONS AND REDUCTION

We obtained 28 time-resolved IR spectra for WZ Sge on 2003 September 6 UT using NIRSPEC[1] on Keck II. NIRSPEC is an all-reflective, near-IR, high-resolution spectrograph for the Keck II Telescope, designed to operate over the wavelength region 0.95–5.4 μm.

We used NIRSPEC in low-resolution mode at one grating setting covering the wavelength range from 2.0 to 2.42 μm, with a slit width of $0\farcs38$, yielding $R = 2200$. The night was clear and appeared photometric, as evidenced by our standard star measurements, and the seeing was near $0\farcs6$ using eyeball estimates from the slit viewer camera. We used the standard four-nod mode of NIRSPEC, in which the star is nodded along the slit at four positions, from which one final spectrum is coadded and written to disk. The scale along the slit length (spatial direction) is $0\farcs143$ (4.2 Å) pixel^{-1}.

We also obtained similar nodded spectra, directly before and after WZ Sge, of the standard star HD 190675 to use for telluric and flux calibration. Flat fields, arc lamps, and dark frames were obtained as well. Data reduction was accomplished in the usual way, for which we used both the NIRSPEC instrument data reduction procedures and our own usual IR spectral reduction

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[1] See http://www2.keck.hawaii.edu/inst/nirspec/nirspec.html.

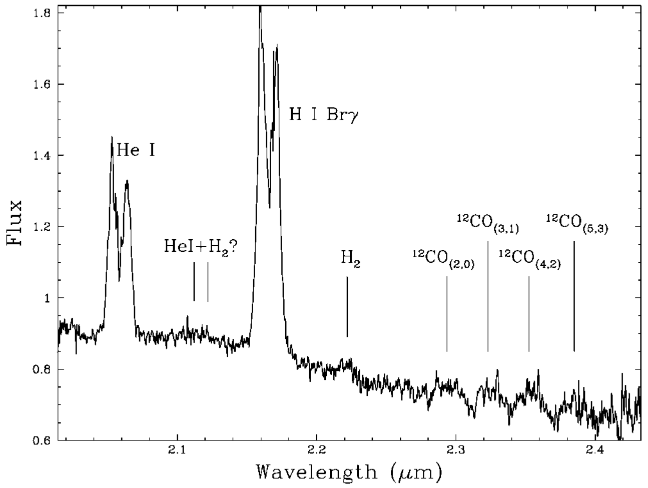

FIG. 1.—Uncorrected, unsmoothed summed spectrum of WZ Sge. H I, He I, and molecular emission due to CO and H_2 are apparent. No absorption features are apparent. The y-axis is relative flux in units of ergs s^{-1} cm^{-2} $Å^{-1}$.

methods (see Harrison et al. 2004b). The two resulting data sets agreed well, with the NIRSPEC reductions being slightly noisier. We estimate our flux uncertainties to be 10%–15%.

While we had hoped that each individual spectrum would be able to stand alone and that most would reveal the secondary star in WZ Sge once and for all, we find that this is not the case. Thus, we were interested in searching for any secondary star features and opted to use summed spectra to increase the S/N. We co-added our 28 spectra into single sums, as well as four distinct orbital phase bins. In this section we discuss features visible in our co-added spectra, and in § 3 we detail their identification and physical nature.

2.1. *Spectral Analysis*

Figure 1 shows our total summed spectrum, with no velocity correction and no smoothing. The salient features are (1) a gentle continuum slope, (2) emission lines of H I and He I, (3) emission features of CO (note that these cannot be the Pfund series in emission; see below), and (4) weak emission centered near 2.12 and 2.20 μm (we identify the latter with H_2; the former is probably a blend of He I and H_2). Table 1 lists measurements of the emission line EWs and FWHM values for the lines seen in Figure 1.

To search for secondary star features, we present in Figure 2 an unsmoothed, radial velocity–corrected, co-added spectrum from all phases. We used the K_2 value given in Steeghs et al. (2001) to determine the secondary's velocity at each phase. We next used the Patterson et al. (2002) ephemeris (also used by Steeghs et al.) to figure out time versus phase. Note that the ephemeris phase 0.0 is photometric phase 0.0; thus we applied the -0.043 phase offset between photometric eclipse and true inferior conjunction to our spectra. We then Doppler-corrected each spectrum to create one median (of 28 individual spectra) spectrum, which we show in Figure 2.

In Figure 2 we see that the H I and He I emission lines appear to have an odd structure, but this is a result of the co-added Doppler corrections around the orbit. We do note that both the strong H I and He I emission lines show very narrow components near line center, and Brγ even has one sitting in its blue wing. Two possible weak absorption lines (from the secondary?) can be seen in Figure 2 at 2.272 and 2.277 μm. These absorptions vary in strength with orbital phase and are stronger at quadrature and during eclipse. However, we caution the reader as to their reality until robust line identifications can be made, although we see similar weak absorption features in the IR spectrum of EF Eri, another short-period CV with a low-mass, cool secondary (Harrison et al. 2003a, 2003b).

TABLE 1
MEASUREMENT OF IR EMISSION LINES

Line	Peak λ (Å)	Equivalent Width (Å)	FWHM (Å)
He I (blue)[a]	20531.4	−31.3	65.4
He I (red)[a]	20636.1	−31.7	73.6
H I (blue)[a]	21604.6	−65.4	70.6
H I (red)[a]	21706.1	−61.0	72.5
H_2	22216.5	−4.4	115.4
$CO_{(2,0)}$	22937.5	−20.7	243.9
$CO_{(3,1)}$	23252.3	−20.7	202.9
$CO_{(4,2)}$	23545.5	−17.7	181.9
$CO_{(5,3)}$	23859.3	−10.6	147.3

NOTE.—By convention, emission lines have negative EW values. The EW values were measured in the phase 0.5 spectrum.

[a] These lines have been deblended using two Gaussian components.

Figure 3 shows co-added, 20 Å boxcar-smoothed spectra for phases 0.0 and 0.5. The phase 0.0 spectrum is produced by only two individual spectra, as this is all we obtained during the short eclipse phase, while the phase 0.5 result was produced from three spectra. We see that the velocities of the emission lines of H I and He I match well at these crossing phases. The phase 0.0 spectrum clearly shows evidence for a strong decline (unmeasureable levels) in the CO emission strength during the eclipse. This is expected for lines produced in the accretion disk, as they will be partially eclipsed by the secondary during this phase. Even though it seems that the secondary star modulates the spectrum during eclipse, no clear signature of any spectral features are detected during phase 0.0.

3. DISCUSSION

3.1. *Hydrogen Emission Lines*

Hydrogen emission from the accretion disk is thought to arise in a chromosphere-like structure skirting the accretion

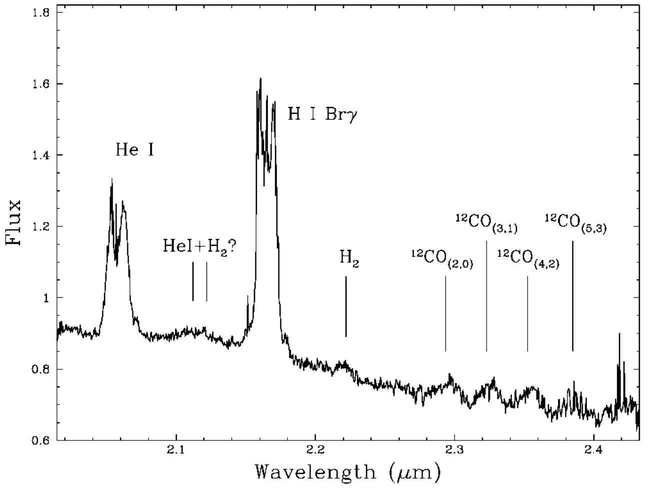

FIG. 2.—RV-corrected, unsmoothed summed spectrum of WZ Sge. We note here the typical H I and He I emission lines. Molecular emission from CO and H_2 are seen as well. Two possible unidentified absorption features (not apparent in Fig. 1 but seen here in the radial velocity–corrected spectrum) are seen at 2.272 and 2.277 μm. The y-axis is relative flux in units of ergs s^{-1} cm^{-2} $Å^{-1}$.

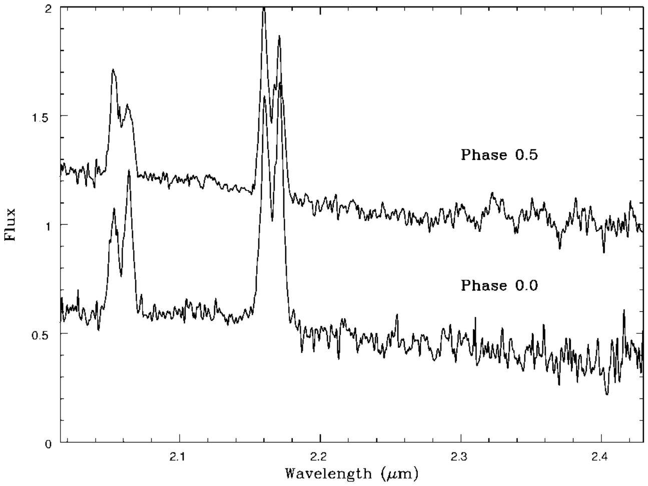

FIG. 3.—Phase 0.0 and phase 0.5 spectra of WZ Sge. The phase 0.0 spectrum is the median of two, and the phase 0.5 spectrum uses three spectra, allowing approximately equal comparison. The data are smoothed by a 20 Å running boxcar. The *y*-axis is relative flux, and the mean levels of the two spectra are 0.0239 (0.5) and 0.0171 (0.0), with the phase 0.0 spectrum offset by −0.2 in flux. The CO emission greatly weakens during the phase 0.0 partial eclipse, indicating an origin in the accretion disk.

disk and/or a (dense) expanding wind (see § 2.7 of Warner 1995). The Brackett emission lines, for example, are seen to be optically thick, as has already been noted in Mason et al. (2000), and emanate from the hotter, denser accretion disk locales, as well as the stream-disk interaction region. Optically thicker H I emission lines are probably produced closer to the plane and/or in the hot spot interacting region, where the temperature is higher while the optically thin Balmer emission arises from the accretion disk "atmosphere." The H I emission line EWs listed in Table 1 compare well with those presented in Mason et al. (2000).

3.2. *Helium Emission Lines*

He I at 2.058 μm is strong and suggests that the 584 Å spectral line is optically thick, indicating an origin in high-density regions within the accretion disk. He I emission is generally believed to come from the inner disk, where the temperature can be high enough to produce it, but in TOADs the inner disk is known to be optically and materially thin (see Mason et al. 2000; Howell et al. 1999). The hot spot is another suggested site for the He I emission, being hot and dense, but the double-peaked nature of the line seems to rule this out as the sole source.

3.3. CO *Emission Bands*

CO emission is rare in astronomical objects. A few early-type, high-luminosity stars, and some compact young stellar objects (YSOs), show CO in emission and share the properties of optically thick Brackett H I emission and the presence of dust emission. These types of objects also contain accretion disks, albeit different in scope to those in CVs (Calvet et al. 1993). WZ Sge is very different in most respects from these classes of objects, but it now joins this small, elite group of astronomical objects with CO emission.

The summed spectra of WZ Sge shown in Figures 1 and 2 clearly show the first-overtone CO bands in emission. It is likely that these emission features are the cause of the rising red continuum seen in previous low resolution *K*-band observations of WZ Sge. We note that the CO emission observed cannot be caused by H I Pfund lines, as the Pfund edge occurs blueward of the first emission band, and blended Pfund emission will not show the band structure we observe.

CO emission is thought to occur by CO-H collision in a relatively dense ($n_{\rm H} > 10^{10}$ cm^{-3}), cool ($T \sim 3000$–5000 K) region. The site of the emission must be separate from locations of ionized hydrogen and helium, as such radiation can easily destroy the CO molecule, with its low dissociation energy of 11.1 eV. Thus, the CO gas distribution does not follow that observed for the H I and He I emission lines (i.e., as inferred by, say, Doppler maps).

Modeling of CO emission in both early-type, highly luminous A and B emission line stars and in embedded young stellar objects has shown that the CO lines are likely to be optically thin (McGregor et al. 1988). The He I (2.05 μm)/H I Brγ ratio in WZ Sge is 0.58, similar to that seen in these early-type, high-luminosity emission line stars. The ratio of the EW of H I Brγ to the first-overtone CO emission band is near 3 for WZ Sge (Table 1), again equal to that observed in the high-luminosity A and B stars and in YSOs. These facts allow us to consider similar line formation conditions in WZ Sge compared with those modeled in the early-type, high−luminosity stars. Therefore, temperatures near, but not much greater than, 3000 K are required to populate these high rotational levels. Given the strength of the CO emission, these same models show that the required vibrational temperatures are in the range of 2000–5000 K, in good agreement with that stated for rotational excitation.

We know in WZ Sge that the CO emission comes from the accretion disk and is not emitted from a larger circumbinary disk. The observational evidence stems from the fact that we see changes (dilution) in the CO emission near phase zero (Fig. 3), a time interval during which the secondary star partially eclipses the accretion disk.

3.4. *Other Spectral Features*

Molecular H_2 emission is likely to arise from similar density and temperature regions within the accretion disk that produce the CO emission. We see H_2 emission in WZ Sge as the typical low-level, broad emission centered near 2.12 (He I+H_2) and 2.22 μm. Confirmation and further study is needed using additional observations, as our continuum S/N does not allow detailed analysis of the H_2 emission.

Observations of early-type, high-luminosity stars and YSOs often show weaker emission due to Fe II, Na I, or Mg II in the near-IR. These lines are thought to be fluorescent emission pumped by H I Balmer continuum emission. We do not see these weaker lines in our data (note that no Fe II lines are in the *K* band), but higher S/N observations would be required.

3.5. *Physical Limits on the Secondary Star*

The distance to WZ Sge is 43.54 ± 0.28 pc (Harrison et al. 2004a), which yields $M_K = 11$, using the out-of-eclipse *K* magnitude of 14.0 (Two Micron All Sky Survey). To assess the contribution to the *K*-band flux from the emission lines, we integrated the spectral flux with and without the H I and He I lines (using the *sbands* program within IRAF) and find that they only contribute 8% of the flux at *K*. Using the phase 0.0 spectrum, we can derive a luminosity limit for the secondary star based on the fact that we do not see any solid spectral evidence for it during this time.

Taking the accretion disk contribution to be ~50% of the

K-band flux, based on (1) the difference between our phase 0.0 and 0.5 spectra, using the fact that it is only a partial eclipse; (2) the detailed disk analysis presented in Mason et al. (2000); and (3) the estimate of a greater than 30% accretion disk contribution to the *K*-band flux as determined by Ciardi et al. (1998), we derive a value of $M_K \geq 12$ for the secondary star. This value suggests that the secondary star is near spectral type L6 V. Normal L6 V brown dwarfs have surface temperatures near 1500 K and masses of $\sim 40 M_J$, both values in accord with the theoretical predictions for WZ Sge's secondary posited by Howell et al. (2001).

4. CONCLUSIONS

The new results found in this study are the identification of CO and H_2 emission from the accretion disk in WZ Sge, and the fact that the outer parts of the disk are as cool as 3000 K during quiescence. The lack of detection of spectral features from the secondary star near phase 0.0, combined with the known distance to WZ Sge, allow a rigorous luminosity limit to be set. We find that the secondary star must be of spectral type L6 V or later. Further high S/N, *K*-band spectroscopy of WZ Sge is needed both to confirm our discovery and to provide detailed spectral information on the molecular emission and for the brown dwarf–like secondary star.

IR observations of other TOADs are needed as well to see if these same disk conditions are present. It is interesting to note here that the accretion disk instability model of Cannizzo & Wheeler (1984) predicts accretion disk temperatures cooler than 5000 K at quiescence, and our findings are the first observational proof that such cool regions exist. Detailed study of the accretion disk CO emission (line shapes, strengths, etc.) would be useful to provide a new physical view into the outer regions of accretion disks, regions invisible to other spectral regimes.

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