EUVE and *VLA* Observations of the Eclipsing Pre-cataclysmic Variable V471 Tauri

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V471 Tauri is an astrophysically important eclipsing binary (K2V+DA2, $P = 12.5$ hr, $d = 50$ pc, 80° inclination) whose understanding is crucial for theories of binary stars evolution. We have observed V471 Tauri with the *EUVE* observatory having the goal to use the hot white dwarf component as a probe of the intra-system material. This would help gain more insight on the nature of the interaction between the two components of the system. V471 Tauri was observed by *EUVE*, the *VLA* and 5 optical telescopes as part of a coordinated campaign from 1994 November 28–December 3 covering approximately 6 orbits of the system. We present light curves and spectra from the *VLA* and *EUVE* portions of the observation using the *EUVE* DS/S Lex/B ($40 - 190$ Å) and the *EUVE* SW ($70 - 190$ Å), MW ($140 - 380$ Å) and LW ($280 - 760$ Å) spectrometers.

A spectrum of V471 Tauri was acquired with the *EUVE* spectrometers from 1994 November 28 to December 2, with a total exposure time of about 100,000 s. We show in Figure 1 the time-averaged spectrum EUV spectrum of V471 Tauri in photon flux units of the combined SW, MW, and LW spectra. In the top part of Figure 1, it is clear the spectral distribution (histogram) is characteristic of that of hot DA star. As expected, some emission lines are detected with He II λ304 Å being the most prominent emission line. Superposed to the spectrum is a fit of pure hydrogen WD model spectra from Vennes (1992) accompanied with the 1, 2, and 3 σ contours in the bottom half of Figure 1. For this fit, $\log g$ is fixed to 8.5 in agreement with the determination of Vennes (1992; based on *IUE* and *EXOSAT* data) and of Kidder (1991). We obtain an effective temperature of $33.1 \pm 0.5 \times 10^3 K$ and an H I interstellar column density of $1.5 \pm 0.4 \times 10^{18}$ cm^{-2} by fitting the spectrum in the $340 - 600$ Å range. Note that the 504 Å photoionization edge of He I is detected from which we measure an ISM column density of $\sim 1.3 \times 10^{17}$ cm^{-2}. Some of the discrepancies at shorter wavelengths are probably due to unaccounted opacities in the atmosphere of the white dwarf that could originate from accretion of material ejected from the K star during flares. Some of the stronger emission lines may be caused by other structures within the system.

In order to understand the origin of the He II λ304 Å emission, we have computed a ligthcurve of this line taking special care to subtract the WD continuum. As shown in Figure 2, the lightcurve is then folded to the orbital period of the system with the hope of finding a correlation between the strength of the line and the orbital phase. The data shows a simple sinusoidal modulation consistent with the maximum emission occurring

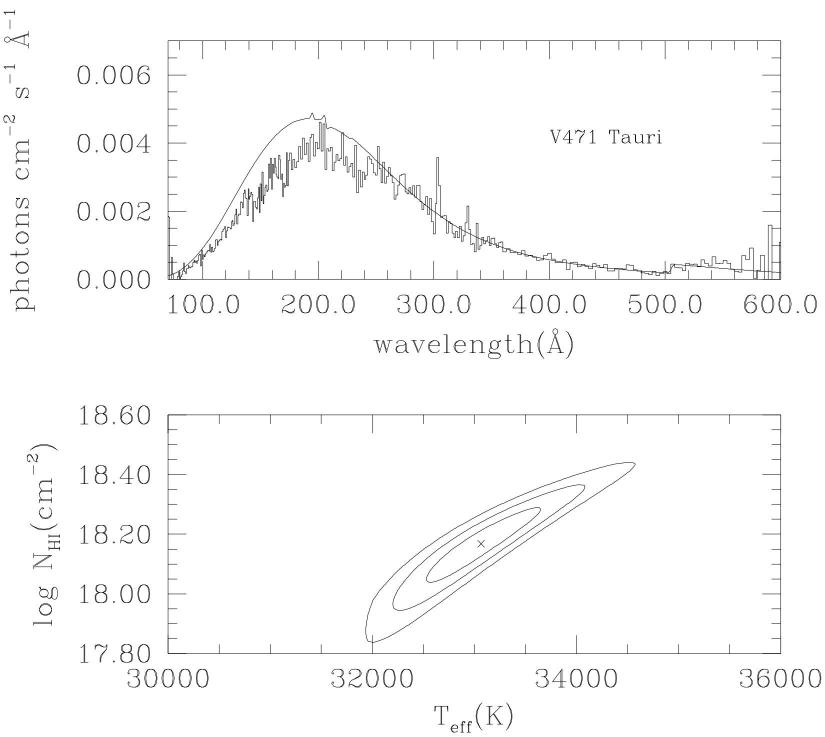

FIGURE 1. (a) Fluxed EUVE spectrum of V471 Tauri (histogram) and best fit pure hydrogen model white dwarf model spectrum with gravity fixed to $\log g = 8.5$. (b) Chi-square contours (1, 2, and 3 σ) for the 2-parameters fit (T_{eff}-$\log g$) shown in Figure 1a.

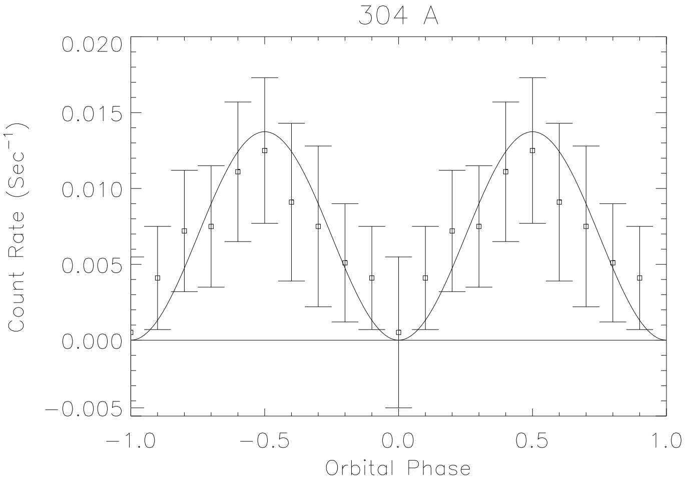

FIGURE 2. He II 304 Å phase binned light curve with fitted sinusoidal modulation

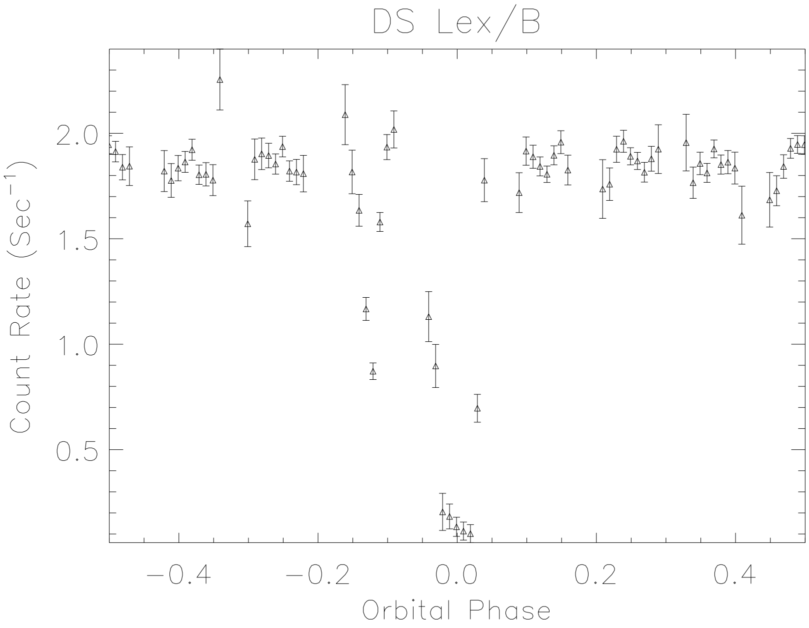

FIGURE 3. EUVE DS Lex/B (40 – 190 Å) phase binned light curve. Note dip at phase −0.12.

when the K star is at superior conjuction. An interpretation of this phenomenon is that the emission consists of reprocessed EUV radiation in the cool star hemisphere illuminated by the hot white dwarf (Thorstensen et al. 1978). This model also explains the variability in V471 Tauri's Hα emission (Young, Skumanich, & Paylor 1988).

V471 Tauri was monitored simultaneously by the *EUVE* Deep Survey (DS) broadband photometer in the Lexan/Boron band (40 – 190 Å). We show in Figure 3 the DS light curve of the entire observation phased on the system orbital period and binned in intervals of 0.01ϕ. The data is dominated by the signal from the white dwarf which can be seen in eclipse at phase 0.0. The width of the eclipse is approximately 0.066ϕ consistent with the optical eclipse and the K2V star radius of 0.85 $R_\odot$ (Young & Nelson 1972). There is a small residual signal within the eclipse which decreases as the eclipse progresses indicating that approximately 10% of the emission from the system is due to the K star.

A strong dip in the light curve is also seen at phase −0.12 lasting for about 0.05ϕ. The dip appeared in the 3rd orbit of the system and lasted until the 6th orbit. At its deepest, in the third and fourth orbits, approximately 90% of the light from the white dwarf was lost. Figure 4 shows the three EUVE integrated spectrometer light curves over the entire observation. The lack of any discernible dip at −0.12ϕ in the LW light curve indicates that the occulting material is heavily ionized since the opacity of neutral hydrogen increases with increasing wavelength in the EUV (Rumph, Bowyer & Vennes 1994). The occurrence of strong dips in both the SW and MW light curves suggests that occulting gas with a temperature of approximately 10^6 K scatters light from the white dwarf out of the line of sight.

Similar transient dips were reported by Jensen et al. (1986) at phases 0.15, 0.18 and 0.85 in an *EXOSAT* observation of this system. The white dwarf line of sight passes by

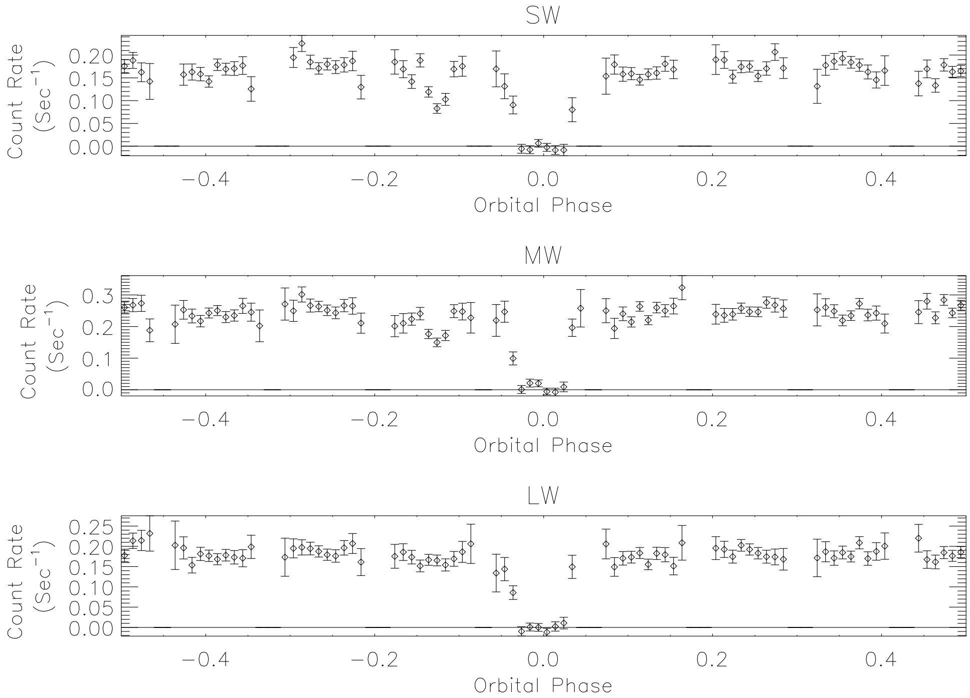

FIGURE 4. Phase binned light curves for the SW (70 – 190 Å), MW (140 – 380 Å) and LW (280 – 760 Å) spectrometers. Note the absence of a dip at phase −0.12 in the LW light curve.

the stable Lagrange points of the system at phases 0.17 and 0.83. We believe the occulter is a large coronal loop from the K star with length comparable to the separation of the 2 stars (3.1 $R_\odot$ Young & Nelson (1972)) located between the stars.

This interpretation is also consistent with the 2.12 hr *VLA* observations (Fig. 5) taken immediately after the *EUVE* observation which show relatively sharp increase/decrease in the 3.6 cm radio emission between $0.15\phi - 0.75\phi$. Lim, White & Cully 1995 have interpreted this increase as being due to an optically,thick extended radio source between the stars with a size comparable to the stellar separation. They have also speculated that the source of the radio emission may be energetic electrons in the K star coronal loop accelerated by magnetic reconnection with the white dwarfs magnetic field at the top of the loop. The same source could also provide substantial heating of the gas within the loop.

It is believed that material is somehow accreted onto the magnetic poles of the white dwarf as evidenced by the 9.25 minute period modulation of the light curve seen by Jensen et al. (1986) and in our observation. This modulation is thought to be due to dark spots formed by the accretion of metals on to the magnetic poles of the white dwarf which rotate in and out of view Clemens et al. (1992). Since the K star in V471 Tauri does not fill its Roche lobe Young & Nelson (1972),no direct mass transfer is possible. However, if large coronal loops from the K star can reconnect with the magnetic field of the white dwarf inside the white dwarf's Roche lobe, accretion of gas from the loop to the white dwarf will result (Lim, White & Cully 1995).

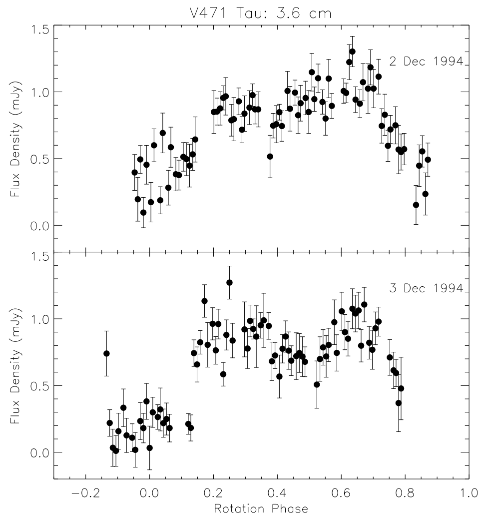

FIGURE 5. Phased binned 3.2 cm light curve taken by the VLA on the two nights following the EUVE observation (1994 Dec 2 and Dec 3)

We thank Stéphane Vennes for providing us with white dwarfs model spectra. We also thank Martin Sirk for computing deadspot corrections for the DS lightcurve. This research was funded by NASA grant NAG5-2641. J.D. is also funded by the NASA EUVE contract NAS5-30180.

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