THE ASTROPHYSICAL JOURNAL, **309**:L27–L31, 1986 October 1

EXOSAT OBSERVATIONS OF V471 TAURI: A 9.25 MINUTE WHITE DWARF PULSATION AND ORBITAL PHASE DEPENDENT X-RAY DIPS

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Received 1986 May 5; accepted 1986 June 24

ABSTRACT

A 28 hr continuous *EXOSAT* observation of the 0.52 day period detached binary V471 Tauri has yielded the detection of a strong, pulsed soft X-ray flux from the white dwarf component, with a 9.25 minute pulse period, an amplitude of 20%, and a double-peaked pulse profile. A residual soft X-ray flux from the K dwarf companion is seen during white dwarf eclipse at orbital phase 0.0. Pronounced dips in the soft X-ray light curve occur at orbital phases 0.15, 0.18, and 0.85. The dips may be correlated with the triangular Lagrangian points of the binary orbit. The X-ray flux from the white dwarf is consistent with thermal models for a white dwarf photosphere with $T_{\rm eff} \approx 35000$ K, $\log g = 8.0$–8.5, $\log[N({\rm He})/N({\rm H})] < -4.5$, and $\log N_{\rm H} = 18.65 \pm 0.2$. The K star has a luminosity of $1.5 \pm 0.3 \times 10^{30}$ ergs s^{-1} in the 0.03–2.5 keV band.

Subject headings: stars: eclipsing binaries — stars: individual — stars: white dwarfs — X-rays: binaries

I. INTRODUCTION

V471 Tauri (BD +16°516) is a well-known 0.52 day binary containing a hot DA white dwarf and a K2 V detached companion. As a member of the Hyades cluster (Young and Capps 1971), it has a presumed age of 5×10^8 yr and a distance of 49 ± 1 pc (Vandenberg and Bridges 1984). Young and Nelson (1972) derived $a \sin i = 1.1 \times 10^{11}$ cm, $\sin i = 79.^\circ 5 \pm 2.^\circ 0$, $M_{\rm K} = 0.8 M_\odot$, $M_{\rm W} = 0.8 M_\odot$, $R_{\rm W} = 6.5 \times 10^8$ cm. The white dwarf mass and radius are accurate to within 15% and are consistent with the Hamada-Salpeter (1961) mass-radius relation for white dwarfs with $\log g = 8.2$–8.5. Model atmosphere fits to *IUE* low-dispersion spectra have determined $T_{\rm eff} \approx 35{,}000$ K and $\log g \approx 8.0$ (Guinan and Sion 1984). The absence of He II, C IV, and Si IV lines in the *IUE* spectra at a sensitivity of 0.5 Å equivalent width constrain the photospheric helium abundance to be $\log[N({\rm He})/N({\rm H})] < -3.0$ and constrain the carbon and silicon abundances to be less than 10^{-1} solar (cf. Henry, Shipman, and Wesemael 1985). The K dwarf's synchronous rotation is one of the most rapid known for a nondegenerate star in a detached system.

Van Buren, Charles, and Mason (1980) identified V471 Tau as a *HEAO* A-2 LED X-ray source. They considered the K star corona to be the likely X-ray source but did not rule out accretion of a K star wind onto the white dwarf. V471 Tau was detected as an *Einstein Observatory* IPC source by Young *et al.* (1983), who also considered the K star to be the probable X-ray source, although their observations did not cover white dwarf eclipse phases.

In this *Letter*, we report new results obtained from a 28 hr continuous observation of V471 Tauri with the European Space Agency *EXOSAT* satellite: the detection of soft X-ray fluxes from both the white dwarf and the K dwarf, the discovery of a 9.25 minute pulsation from the white dwarf, and the discovery of orbital phase related soft X-ray dips.

II. OBSERVATIONS

The *EXOSAT* X-ray observatory was pointed at V471 Tauri continuously from UT 1551 on 22 August 1985 to UT 1954 on 23 August 1985, covering 2.24 binary orbits, including two white dwarf eclipses. During this time, 26.9 hr of data were obtained by the CMA at the focus of the LE1 telescope (de Korte *et al.* 1981), which was sensitive in the 0.03–2.5 keV bandpass. The thin lexan, aluminum, thick lexan, and boron filters were used. V471 Tau was detected in all but the boron filter. A weak 2–6 keV flux was detected by the medium energy (ME) detectors. We defer a report on this harder X-ray flux to a forthcoming paper.

a) *Soft X-Rays from Both Stars*

The LE light curve for the entire observation is shown in Figure 1. The decline in the soft X-ray flux during the white dwarf eclipses, centered at phases 1.0 and 2.0, indicates that most of this flux comes from the white dwarf, although there is a residual soft X-ray flux from the K star. The sharpness of the X-ray eclipse is consistent with the 1 minute interval

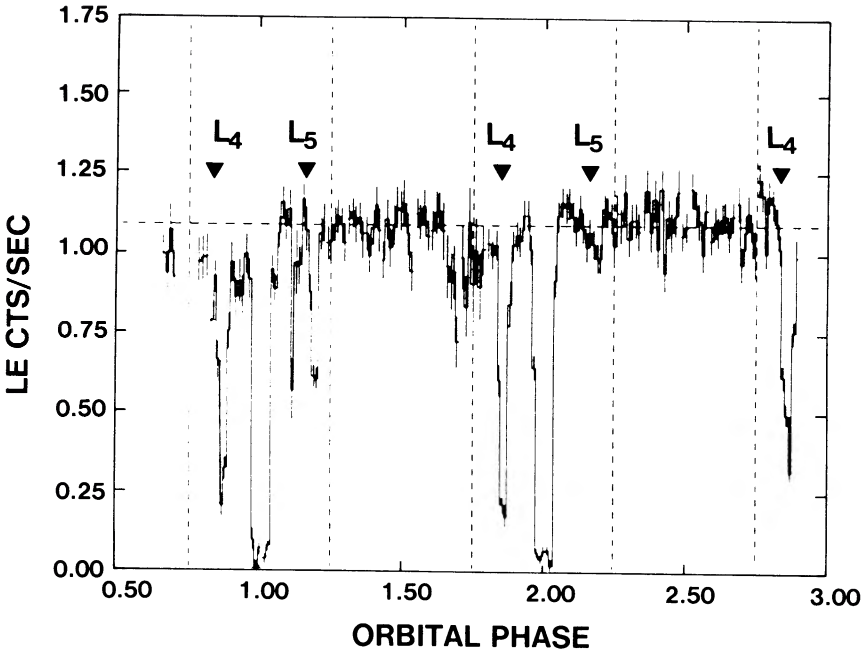

FIG. 1.—Light curve of the 0.03–2.5 keV flux from V471 Tauri for the 28 hr observation in 554.85 s bins (one pulse period). The thick lexan and aluminum filter data were normalized with respect to the thin lexan filter rate (see Table 1). The horizontal dashed line indicates the mean thin lexan count rate between orbital phases 0.22 and 0.62, which we identify as a "clean" flux level. The vertical dashed lines mark the phases of quadrature. The phases at which the triangular Lagrangian points (L_4 and L_5) are in our line of sight to the white dwarf are indicated by the arrows.

TABLE 1

EXOSAT LE COUNT RATES

Filter	Total Rate (s^{-1})	K Star Rate[a] (s^{-1})	White Dwarf Rate (s^{-1})
Thin lexan	1.093 ± 0.014	0.0456 ± 0.0063	1.047 ± 0.016
Aluminum	0.810 ± 0.011	0.0182 ± 0.0073	0.792 ± 0.013
Thick lexan ...	0.636 ± 0.010	0.0319 ± 0.0154	0.604 ± 0.018
Boron[b]	< 0.009	< 0.009	< 0.009

[a] K star rates with thin lexan and thick lexan filters were measured during white dwarf eclipses. The aluminum rate is estimated from the thin lexan rate, using 0.3–2.0 keV thermal spectra with log N_H = 18.7.

[b] No detection with the boron filter. The upper limit is 3σ. Distinction between the K star and white dwarf is not possible.

between optical contacts (Beavers, Oesper, and Pierce 1979). The count rates observed or estimated from each star in each of the four filters are given in Table 1.

b) *Soft X-Ray Dips*

Pronounced dips in the soft X-ray flux at orbital phases 0.15, 0.18, and 0.85 can be seen in the LE light curve (Fig. 1). The phase 0.85 event is the strongest, with essentially complete cutoff of the white dwarf flux at the depth of the event. It occurs from three successive binary orbits. The phase 0.15 event occurs during the first orbit, but is gone 12.5 hr later. The phase 0.18 event also occurs during the first orbit, and is greatly diminished 12.5 hr later. There is also a broader, more shallow flux decrease between phases 0.62 and 0.83 during the first two orbits. This decrease does not occur during the next orbit.

c) *White Dwarf Pulsations*

A Fourier analysis of the LE flux has revealed a 9.25 minute periodic variation (Jensen 1985). A power spectrum for data obtained during the "clean" phases 0.22–0.62 is shown in Figure 2. There is more power in the first harmonic at 3.60 mHz than in the 1.80 mHz period. We have examined the power spectrum out to the ninth harmonic and find no other harmonic to have power significant at greater than 90% confidence. This constrains the power in any of these harmonics to be less than 30% of the power in the fundamental. The inset in Figure 2 shows the pulse profile for the subset of "clean" data obtained with the thin lexan filter. It is double peaked, accounting for the strength of the first harmonic. The count rate at pulse minimum is ~ 80% of the count rate at pulse maximum.

III. DISCUSSION

a) *The X-Ray Fluxes*

The soft X-ray fluxes from white dwarfs have generally been successfully fit by photospheric models (Kahn *et al.* 1984; Heise 1985; Petre, Shipman, and Canizares 1986). The white dwarf rates listed in Table 1 were fitted using white dwarf model atmospheres for $T_{\rm eff}$ = 30,000 K, 32,500 K, and 35,000 K, and log g = 8.0 and 8.5 to test the possibility that the soft X-ray flux from the white dwarf in V471 Tau is photospheric in origin. Details concerning the model atmospheres we used can be found in Petre, Shipman, and Canizares (1986). Since the photospheric temperature, gravity, and distance to the source are known approximately, the observed

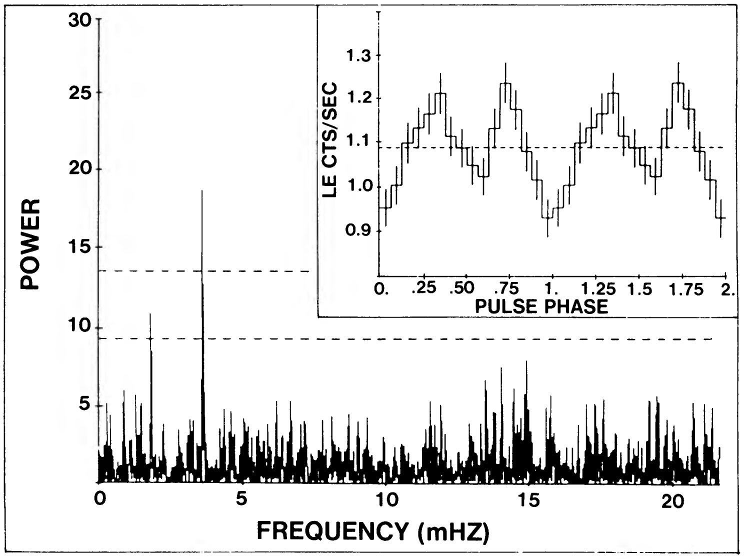

FIG. 2.—Power spectrum of the 0.03–2.5 keV flux for all data collected between orbital phases 0.22 and 0.62, normalized with respect to the thin lexan filter rate. The power is normalized with respect to the Poisson noise level. The Nyquist frequency is 86.51 mHz. The frequency resolution is 0.01056 mHz. The higher frequency power (*unshown*) is consistent with a Poisson noise process. The two horizontal dashed lines indicate the minimum power levels for which features exceed Poisson noise expectations at confidences of 50% and 99%. The pulse profile (*inset*) was obtained by folding the subset of "clean" data obtained with the thin lexan filter, using a 554.85 s period.

TABLE 2

WHITE DWARF MODEL ATMOSPHERE FITS

T_{eff}(K)	log g	Successful Fit?	$\chi^{2\,\mathrm{a}}$ Minimum	log N_{H} (cm^{-2})	log[N(He)/N(H)]
30,000	8.0	No	> 179	...	...
	8.5	No	> 154	...	...
32,500	8.5	Almost	7.5	~ 18.5	Pure hydrogen
35,000	8.0	Yes	2.8	18.69 ± 0.02	−4.6 ± 0.07
	8.5	Yes	< 2.5	18.77 ± 0.03	< −5.4

[a] Minimum χ^2 for a grid of N_{H} and N(He)/N(H). Errors of N_{H} and N(He)N(H) are 99.9% confidence for 1 degree of freedom.

EXOSAT count rates for the three filters provide good constraints on the chemical composition of the photosphere and the interstellar column density. To model the composition of the photosphere, we varied the helium abundance as $\log[N(\mathrm{He})/N(\mathrm{H})] = -5.3$ to -3.7 in steps of 0.1 dex. A pure hydrogen atmosphere model was also tested. We have assumed a negligible opacity due to metals heavier than helium. Simulations show that metal abundances greater than 10^{-3} solar produce a significant opacity at 50 eV (Kahn *et al.* 1984). Until more sensitive UV spectra are obtained, we cannot rule out the possibility that photospheric metal opacity has an effect on the emergent soft X-ray flux.

The results from our fits are summarized in Table 2. Successful fits are found for $T_{\mathrm{eff}} = 35{,}000$ K and $\log g = 8.0$ and 8.5. A $T_{\mathrm{eff}} = 32{,}500$ K, $\log g = 8.5$ model almost fits, suggesting that a finer grid of models would show a slightly higher temperature to be within acceptable bounds. The agreement between the *EXOSAT* data and white dwarf model atmospheres, for temperatures and gravities consistent with UV observations, provides evidence that the soft X-ray flux from the white dwarf in V471 Tau originates in a $T_{\mathrm{eff}} \approx 35{,}000$ K photosphere which may contain trace elements of helium and/or heavier metals. The successful photospheric models give a 0.03–2.5 keV white dwarf flux of $3 \pm 1 \times 10^{-11}$ ergs cm^{-2} s^{-1}, corresponding to a luminosity of $4 \pm 1 \times 10^{31}$ ergs s^{-1}. Because the white dwarf flux is pulsed, it is probable that a fit of a homogenous photospheric model to the pulse averaged count rates does not correctly constrain the "average" photospheric parameters. Additional fits of more complex photospheric models are in progress.

The K star has a migrating RS CVn type wave (Young *et al.* 1983, and references therein), which implies spotted regions and a high density of magnetically confined coronal plasma. Its corona is presumably similar in nature to those of other active late-type stars observed by the *Einstein* and *EXOSAT* Observatories, and is describable in terms of thermal emission with kT in the range 0.3–2 keV (e.g., Golub 1983). The observed ratio of rates in the thick and thin lexan filters is consistent with temperatures in this range for interstellar column densities of $1\text{–}7 \times 10^{18}$ cm^{-2}, which are also consistent with the white dwarf models. The implied 0.03–2.5 keV K star flux is $\sim 6 \times 10^{-12}$ ergs cm^{-2} s^{-1}, corresponding to a luminosity of 1.5×10^{30} ergs s^{-1}.

b) *The Dips*

The lines of sight to the white dwarf during the dips are illustrated in Figure 3, which shows that material located along these lines of sight was at least 2–3 stellar radii from the K star. The broad dip at phases 0.62–0.75 must be due to material located closer to the white dwarf than to the K star. Figure 3 shows that the dips at phases 0.15, 0.18, and 0.85 occurred when the triangular Lagrangian points of the binary orbit are near the line of sight to the white dwarf. These

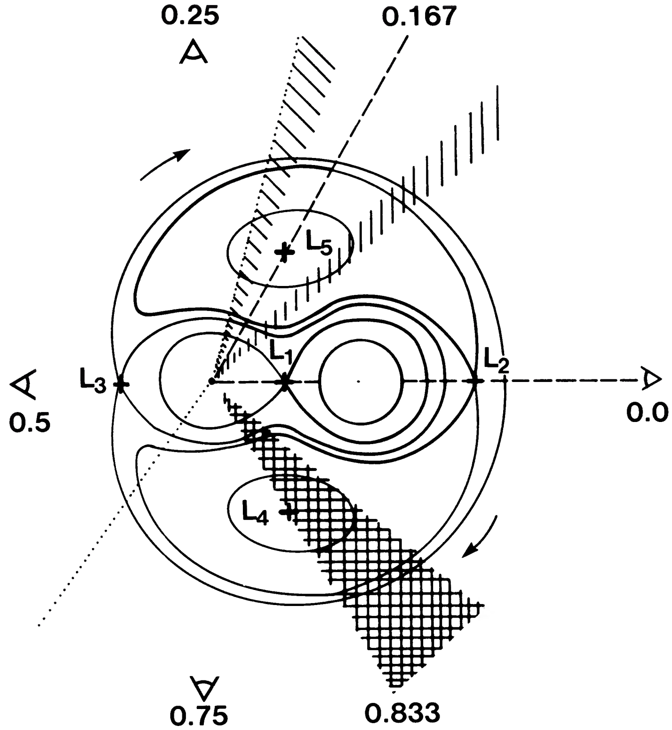

FIG. 3.—Schematic of the V471 Tauri binary system, indicating the orientations of the five Lagrangian points, and their Roche equipotentials, with respect to the white dwarf and K star components. A mass ratio $q = 1$ is used. The K star clearly does not fill its Roche lobe. The curved arrows indicate the sense of rotation of the system. The dotted lines mark the orbital phase range for which dips are seen in the 0.03–2.5 keV light curve. The lines of sight to the white dwarf at the triangular Lagrangian phases (0.167 and 0.833) are indicated by dashed lines, as is the eclipse phase 0.0. The shaded regions indicate the phases at which dips are seen. The dip near the L_4 point is particularly deep and persistent, and is therefore more heavily shaded.

unique phases are 0.83 for the Lagrangian point on the ingress side (L_4) and 0.17 for the point on the egress side (L_5) (Kopal 1978). It is possible that ejected material collects at these potential minima. Alternatively, the material could be in very large coronal loops anchored to the K star. Another possibility is that absorbing material is located at greater, circumbinary distances. Bruhweiler and Sion (1986) have suggested the presence of cool circumbinary material in this system. There is not sufficient coverage of the dips in the thick lexan and aluminum filters to permit a spectral analysis. An additional cold absorbing column of 1.5×10^{19} cm^{-2} would reduce the flux observed with the thin lexan filter by e^{-1}. Absorption dips in neutron star low-mass binary systems have been attributed to structures related to accretion disks (e.g., White and Mason 1985). There is no evidence in the V471 Tau UV data for an accretion disk (Guinan and Sion 1984).

c) *The White Dwarf Pulsations*

We consider the most likely cause of the pulsations to be either (1) the rotation of a nonhomogenous photosphere, with the inhomogeneity produced by mass accretion onto magnetic polar regions of the white dwarf, or (2) nonradial *g*-mode oscillations excited by an instability in the photosphere.

i) *Rotation?*

The double-peaked pulse profile is suggestive of a bipolar structure in the white dwarf photosphere, which could be readily explained if it is accreting mass from the K star onto magnetic polar regions. The mass accretion rate should determine whether the poles are bright or dark in X-rays. For example, a rate of $10^{-11.5} M_\odot$ yr^{-1} could product 12.5 eV polar hot spots with a filling factor of $10^{-3.5}$. A blackbody flux from such spots would be consistent with the *EXOSAT* data, but the required accretion rate is high for a detached binary in which the mass transfer is through capture of the K star wind. Accretion rates $< 10^{-12} M_\odot$ yr^{-1} would not produce polar hot spots bright enough to modulate the soft X-ray flux but may supply sufficient helium or metals to produce dark spots. Sion and Starrfield (1984) have suggested that the photospheric metal lines observed in the hot DAZ white dwarf Feige 24 are supplied by accretion from the detached M dwarf companion.

Accretion/diffusion models for V471 Tau are required to determine whether dark poles can be produced by reasonable mass accretion rates in competition with radial and lateral diffusion. The white dwarf magnetic field does not have to be as strong as the fields in magnetic cataclysmic variables to be able to channel these lower accretion flows onto the poles.

ii) *Oscillations?*

The instability of white dwarf photospheres to nonradial *g*-mode oscillations, excited by the κ-mechanism in partial ionization zones, is well established for DA white dwarfs sufficiently cool ($T_{\rm eff} < 12{,}000$ K) to have unstable hydrogen partial ionization zones, the ZZ Ceti variables (Winget *et al.* 1982*a*). The discovery of DB pulsators with $T_{\rm eff} \approx 30{,}000$ K (e.g., GD 358, Winget *et al.* 1982*b*, and PG 1654+160, Winget *et al.* 1984) confirms the existence of a helium instability strip near this temperature. Given the extreme sensitivity of the temperature of the helium instability strip to the efficiency of convection (Winget *et al.* 1983), it is possible that DA white dwarfs with $T_{\rm eff} \approx 35{,}000$ K and a stratified H/He atmosphere could be unstable to nonradial *g*-mode oscillations driven by a helium partial ionization zone beneath a thin hydrogen surface layer. Cox and Starrfield (1986) and Kawaler (1986) have recently argued that nonradial *g*-mode oscillations in hot DA white dwarfs could be driven by nuclear burning.

IV. FINAL REMARKS

Additional *EXOSAT* observations of V471 Tau in 1986 February confirm the existence of the 9.25 minute pulsations. The pronounced dips, which were prominent in the 1985 August observation, were not evident in the 1986 February observations. A more detailed analysis and discussion of all of the *EXOSAT* observations of V471 Tau will appear in a forthcoming *Letter*.

This work was supported by a NASA grant from the Office of Solar and Heliospheric Physics (K. A. J.), NASA grant NAG5-343 to Villanova University (E. M. S.), NASA grant NAG8-564 (H. L. S.), and NSF grant AST81-15095 (H. L. S.).

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