THE ASTROPHYSICAL JOURNAL, 374:707–720, 1991 June 20

INEFFICIENT ACCRETION BY THE DA2 WHITE DWARF IN V471 TAURI

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Received 1990 March 19; accepted 1990 December 12

ABSTRACT

We report the results of an analysis of eight high-resolution *International Ultraviolet Explorer* (*IUE*) SWP (1200–2000 Å) spectra of V471 Tauri, an eclipsing-spectroscopic, precataclysmic binary in the Hyades. The technique utilized was the co-addition in velocity space of regions surrounding principal high-excitation and low-excitation ion species on a common velocity scale. Certain images were compensated for the orbital motion of the white dwarf during the exposure. In our search for absorption features in these spectra, we find that identifiable lines fall into three categories: (1) interstellar absorption in the line of sight to the Hyades cluster, (2) broad features due to absorption by the stellar wind from the K2 dwarf, and (3) narrow, high-velocity, circumbinary absorption independent of orbital phase. We can detect no evidence for photospheric absorption lines in the white dwarf with equivalent widths greater than a limiting value of 50 mÅ. We estimate that if the hydrodynamic considerations of Bondi & Hoyle were an appropriate description of accretion, the white dwarf in V471 Tauri should have accreted some 3×10^4 times more material than the upper limits which we have determined. In the absence of strong evidence for accreted photospheric heavy elements at the Einstein-redshifted velocity of the white dwarf surface layers we propose, as a possible explanation, that the barrier presented by the white dwarf's rotating magnetosphere reduces accretion from the K2V stellar wind to levels which are undetectable with the *IUE* satellite.

Subject headings: hydromagnetics — stars: accretion — stars: individual (V471 Tauri) — stars: white dwarfs — ultraviolet: spectra

1. INTRODUCTION

V471 Tauri (BD +16°516) is a single-line spectroscopic binary which undergoes total eclipses in the course of its 12.5 hr orbit. The visible spectrum contains Ca II H and K lines with strong emission cores, and the ultraviolet continuum is "unusually strong" (Nelson & Young 1970). The absorption lines in the visible spectrum are greatly broadened by rotation, so much so that it is difficult to assign a spectral type based on the line strengths. On the basis of the $U-B$, $B-V$ colors, the visible light is ascribed to a normal K2 main-sequence star (Young & Nelson 1972), with nominal mass 0.80 $M_\odot$ and nominal radius 0.85 $R_\odot$. The mass function of the system is 0.19 $M_\odot$ (Young & Nelson 1972). The separation of the components is 2.2×10^6 km, i.e., 3.7 times the radius of the K dwarf (Young & Nelson 1972). The secondary star must be compact: the duration of ingress into, and egress out of, the total eclipse takes only 58 s in time (compared to 47.2 minutes for the duration of the total eclipse). These results indicate that the secondary star has a radius no more than ~1% of the K dwarf radius (Young & Nelson 1972), putting it in the realm of white dwarfs. On the basis of X-ray fluxes, the best solution for the secondary star is a DA2 white dwarf (Jensen *et al.* 1986) with effective temperature ~35,000 K. The system is a member of the Hyades, with an age therefore of order 10^9 yr, and the white dwarf progenitor must have had a mass of at least 2.5 $M_\odot$ (Young & Nelson 1972).

In this paper, we are interested principally in examining the implications of mass accretion onto the white dwarf from its K2 dwarf companion. The possibility that the white dwarf in V471 Tauri is accreting material has been suspected recently on several fronts but direct observational evidence of its actual existence remains elusive. The physical dimensions of the system are such that we can be rather confident that the K2 dwarf does *not* overflow its Roche lobe: therefore the white dwarf is *not* subject to the sort of heavy mass transfer which is characteristic of cataclysmic systems. However, this does not mean that the white dwarf is therefore situated in a region of space which is free of mass flow. To the contrary, the K2 dwarf has been found to be losing mass in the form of a measurable wind (Mullan et al. 1989), with $\dot{M} \geq 2 \times 10^{-11}$ $M_\odot$ yr^{-1} and speed $V_w \approx 600$ km s^{-1}. In the presence of such a wind from its close companion, the white dwarf might be expected to accrete material by gravitational capture at a rate significantly higher than that expected from interstellar accretion onto single degenerates.

The first discussion of possible evidence for accretion in V471 Tauri appeared in the context of the discovery of a 9.25 minute periodicity in its X-ray flux (Jensen et al. 1986). The X-ray flux originates predominantly in the white dwarf photosphere, and the discoverers of the X-ray periodicity interpreted it in terms of accretion as follows: if heavy elements accrete onto the magnetic poles of an obliquely rotating DA white dwarf, these poles could become "dark" in X-rays (because the otherwise pure hydrogen envelope, which is highly transparent to soft X-rays would become "poisoned" by matter which is highly opaque to such X-rays), and the periodicity would arise from rotational modulation. The 9.25 minute periodicity has since also been detected in optical data (Robinson, Clemens, & Hine 1988). However, according to a different point of view, the 9.25 minute periodicity in X-rays and optical may have nothing to do with rotational modulation. For example, it may instead be due to nonradial pulsations of the white dwarf: the latter interpretation is favored if multiple periodicities are indeed present. The presently available optical power spectra (e.g., Winget & Claver 1989) may suggest the existence of multiple periods, although the statistical significance of the multiple peaks does not seem altogether convincing. Thus although nonradial pulsations may be a plausible interpretation of optical variations in V471 Tauri, rotational modulation cannot yet be definitely ruled out as an explanation of the 9.25 minute X-ray variations.

Further indirect evidence suggesting the occurrence of accretion is the recent discovery of a cool expanding circumbinary shell at -1200 km s^{-1} in the line of sight to V471 Tauri which may be related to an accretion-triggered thermonuclear runaway on the white dwarf (Sion et al. 1989).

The possibility of using detached post–common envelope red dwarf–white dwarf close binaries as accretion "laboratories" and as an indirect means of establishing red dwarf wind/flare mass loss, has been explored by Sion & Starrfield (1984). Low-resolution *IUE* spectra of V471 Tauri taken at orbital phases when the white dwarf is not shining through K2V transition region structures (0.18–0.85), occasionally exhibit absorption lines. In one series, (SWP 25304L and SWP 25307L), Si IV appears in absorption (E.W. = 0.5–1.0 Å) in two sets of back-to-back large- and small-aperture *IUE* low-resolution spectra long before ingress and egress of primary eclipse (Guinan et al. 1986). While these transient absorptions may be due to intrasystem gas absorbing white dwarf continuum, a photospheric origin cannot be ruled out and the implications of a photospheric interpretation have been discussed by Sion (1986) in the context of the 9.25 minute X-ray oscillations.

All of the observed phenomena mentioned above, together with a critical need to achieve a more basic understanding of accretion physics, motivated us to undertake an intensive search for evidence of accreted heavy elements and/or helium at the photosphere of the DA2 star, using SWP high-resolution IUE spectra of the white dwarf. This search began with the first three high-resolution SWP spectra obtained by Beavers (1982), whose objective was to use detected metals to obtain a radial velocity curve for the DA2 star. Using these same images with velocity co-addition techniques, Bruhweiler & Sion (1986) found no evidence for photospheric heavy elements, thus confirming Beaver's negative result, but they did find evidence of a cool, high-velocity, circumbinary shell at -590 km s^{-1}.

The search for photospheric helium and heavy elements was enlarged with a comprehensive *IUE* observing program utilizing better exposed SWP images and employing a technique to compensate for the orbital motion of the white dwarf during the exposure. In this paper we report the results of this search and present stringent abundance limits for two critical ion species. In § 2, a description of our observing strategy and techniques of analysis is presented as well as a log of all SWP high-resolution spectra. In § 3 we present the results of the search for metal lines. In § 4 we discuss various mechanisms which may help to explain the negative results of our search. In § 5, we summarize the work.

2. OBSERVATIONS AND ANALYSIS

All the observations discussed in this paper were obtained with the *IUE* satellite using the short-wavelength prime (SWP) camera in the high-dispersion echelle mode. The resolution of these high-dispersion spectra ($\lambda/\Delta\lambda \approx 2 \times 10^4$) is such that 1 pixel at the C IV λ1550 lines corresponds to 0.08 Å, i.e., a velocity width of $\sim$15 km s^{-1}. Three of the images were in the *IUE* archives and were originally obtained by W. Beavers. Five other high-resolution images were obtained by Sion & Bruhweiler of which three were velocity-compensated for the orbital motion of the white dwarf. This procedure consisted of dividing the exposure into numerous segments of $\sim$10 minutes each. Between each 10 minute segment the exposure was interrupted so that the target could be moved to a different position along the dispersion direction in the large aperture. These positions were chosen so that the variation in velocity of the white dwarf due to its orbital motion during the exposure, would be compensated in the spectrum. In Table 1, a log of the SWP spectral observations is presented with the tabulated entries as follows: SWP image number, year and day number of observation, exposure time in minutes, orbital phase at midpoint of exposure, phase range covered by the exposure, and comments.

The data were analyzed interactively at the NASA Goddard Space Flight Center Regional Data Analysis Facility (RDAF) using standard software and via a phone link between the RDAF VAX408 computer and Villanova University. In order to optimize the possibility of detecting weak features arising in the white dwarf photosphere and avoid confusion with any K2V emission, or with interstellar/circumstellar absorption features, all but two of the images were taken near times of maximum radial velocity (quadrature phases). In order to further enhance the possibility of detecting weak velocity-shifted features due to the white dwarf, we co-added ions of the same multiplet or of similar excitation in velocity space. This procedure, for a given set of ions, consisted of extracting the region with IUEHI, converting to velocity space with VELSPC, storing the arrays with IUESAVE, mapping onto a common wavelength (velocity) scale using MULTERP, and co-adding in velocity space with the routine COADD. All of these procedures are documented in the *IUE* data reduction manual (RDAF Staff 1989), except for VELSPC. The above procedure was applied to the highly ionized resonance doublets of Si IV $\lambda\lambda$1393, 1402 and C IV $\lambda\lambda$1548, 1550 as well as to O I λ1302, C II λ1335, and Si II λ1260. Other wavelength regions including that around He II λ1640, were searched in velocity space but without co-addition.

3. RESULTS

Using the procedures described in § 2, we carried out an exhaustive examination of the images in Table 1 for any evidence of the white dwarf photospheric absorption features with the rest wavelengths listed above.

3.1. *Expected Locations of White Dwarf Photospheric Lines*

Where should we look for white dwarf photospheric features in the spectra? The answer depends on the orbital velocity v_{orb} of the white dwarf at the time when the spectrum was obtained and also on the gravitational redshift (corresponding to a positive velocity v_g). Of these, the orbital velocity can be estimated

TABLE 1

High-Resolution SWP Observations of V471 Tauri

SWP Image Number	Year/Day Number	Exposure Time (minutes)	ϕ	$\Delta\phi$	Comments
15898	1981/362	181	0.75	0.24	Poor S/N
15899	1981/363	114	1.0	0.15	Poor S/N
15900	1981/363	207	0.24	0.28	Fair S/N
28826	1986/216	250	0.71	0.32	Noisy
31611	1987/234	190	0.22	0.25	Velocity compensated
31630	1987/236	390	0.33	0.52	Circumbinary
32649	1988/001	186	0.77	0.25	Velocity compensated
32659	1988/003	217	0.75	0.29	Velocity compensated

once we know the phase at which each spectrum was obtained (see Table 1) and the mass ratio M_{wd}/M_K of the binary. (The system is a single line spectroscopic binary, with only the K dwarf radial velocity being directly measurable.) The phase of each exposure can be converted to v_{orb} using the K dwarf radial velocity curve of Young & Nelson (1972). The ephemeris given there, although old, remains sufficiently accurate for our purposes. In any event, as much as 30 s jitter in eclipse timings will not effect the velocities corresponding to our exposures, which lasted more than 1 hr each.

Estimation of v_g requires knowledge of the white dwarf mass M_{wd}. Young & Nelson (1972) estimate $M_{wd} = 0.8\ M_\odot$ (and mass ratio therefore 1.0). Using standard white dwarf models, this yields $v_g \approx 50$–60 km s^{-1}. Subsequently, Young & Lanning (1975) revised the elements and suggested $M_{wd} = 0.72\ M_\odot$ (and therefore mass ratio 0.9), and $r_{wd} = 0.012 r_\odot$: these values lead to $v_g \approx 40$ km s^{-1}. Thus, even if we know the orbital velocity precisely, we need to examine a range of possible velocities (corresponding to v_{orb} + 40–60 km s^{-1}) in the co-added spectra.

How uncertain is the mass ratio for V471 Tauri? If we were to admit so much uncertainty in the white dwarf mass that it might be equal to the smallest known white dwarf mass (an extreme assumption), i.e., 0.4 $M_\odot$, the mass ratio for V471 Tauri would be 0.5, and the value of v_g would fall to 20 km s^{-1}. In this regard, we note that very recently, Young (1991) has suggested that the white dwarf mass in V471 Tauri may be of order 0.4 $M_\odot$ if certain features in Hα spectra of this system are due to material at the inner and outer Lagrangian points. However, this conclusion is subject to confirmation, particularly since it seems difficult to reconcile it with the mass function of 0.19 $M_\odot$ (Young & Nelson 1972): if the mass of the K dwarf is indeed 0.8 $M_\odot$, then the mass of the white dwarf cannot be less than 0.75 $M_\odot$ with the above mass function. And even if M_K is as small as 0.5 $M_\odot$ (or as large as 1.0 $M_\odot$), a mass function of 0.19 $M_\odot$ requires M_{wd} of 0.6 (or 0.9) $M_\odot$. Thus, it appears that the minimum value of the mass ratio cannot be less than 0.9 unless the mass of the K dwarf is seriously in error. However, to be as conservative as possible in evaluating where we should be looking for white dwarf features, we will consider the possibility that the mass ratio might be as small as 0.7: this should certainly provide an extreme range of permissible values to search in velocity at any particular phase of the orbit.

For example, let us consider orbital phase 0.75, where the effects of uncertainties in mass ratio have maximal effect on predictions of v_{orb} for the white dwarf. At this phase, the K2 dwarf has a velocity of -100 km s^{-1} (e.g., Bois et al. 1988), but the systemic velocity is $+40$ km s^{-1} hence, the amplitude of the K2 dwarf motion is -140 km s^{-1} relative to the center of mass. Therefore, with a mass ratio of unity, the white dwarf at this phase would have $+140$ km s^{-1} relative to the center of mass, corresponding to a heliocentric velocity of $v_{orb} = +180$ km s^{-1}: adding $v_g = 40$–60 km s^{-1} to this, we find that we should search the velocity range from $+220$ to $+240$ km s^{-1}. But if the mass ratio were to have the extreme value of 0.7 (with v_g about $+20$ km s^{-1}), at phase 0.75 the white dwarf would have $v_{orb} = +240$ km s^{-1}, and the sum of this with v_g would be $+260$ km s^{-1}. Thus, in order to cover the extreme range of mass ratios, we will search over the velocity range of $+220$ to $+260$ km s^{-1} at phase 0.75, i.e. an extreme uncertainty of less than 50 km s^{-1}. This must be regarded as a liberal allowance for velocity uncertainties. At other phases in the orbit, the velocity uncertainty will be smaller than 50 km s^{-1}.

Now, we note that a velocity range of 20 km s^{-1} corresponds to 1.3 pixels in our *IUE* spectra. Thus, even with an extreme uncertainty of 100 km s^{-1} in the velocity range, this amounts to ~6 *IUE* pixels. Since we cannot in any case trust a spectral feature which is less than a few pixels in width, the above uncertainties in the velocity range turns out to be not very restrictive in practice when we interpret our *IUE* spectra. Moreover, the spectra which will be illustrated in the figures below have all been subjected to five-point smoothing before plotting in order to improve the signal/noise ratio: by this means, we are smoothing over some 75 km s^{-1} in velocity space, and therefore automatically covering almost the entire range of velocity uncertainty. In effect, we need to examine only a few pixels in our phase-defined velocity window in the smoothed spectra in order to identify the locations which should be occupied by features on the surface of the white dwarf. The most conservative upper limits on the equivalent widths of narrow metallic absorption lines will be set by the largest noise fluctuations over the permissible velocity window in each spectrum.

3.2. *Identifiable Absorption Lines in Our Spectra*

In our search for absorption lines, although we could define the velocity windows for white dwarf photospheric features fairly well, we actually searched for spectral features over a much broader range of velocities, from -1500 to $+1000$ km s^{-1}.

In Figures 1a and 1b we display typical co-added velocity plots in the region of Si IV and C IV, respectively, for SWP 32659 with the two doublet components of each ion co-added. This image was selected because it was carefully compensated for the white dwarf orbital velocity and its exposure time was sufficiently long to have good signal to noise, yet the spread in orbital phase during the exposure was short enough to ensure

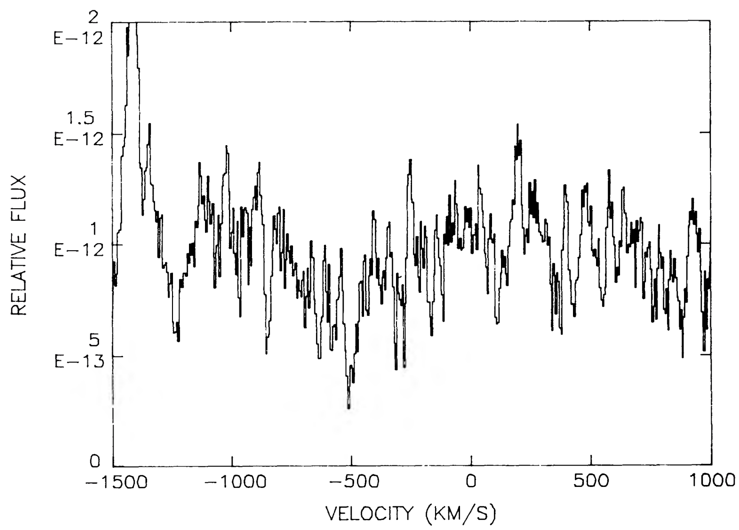

FIG. 1*a*

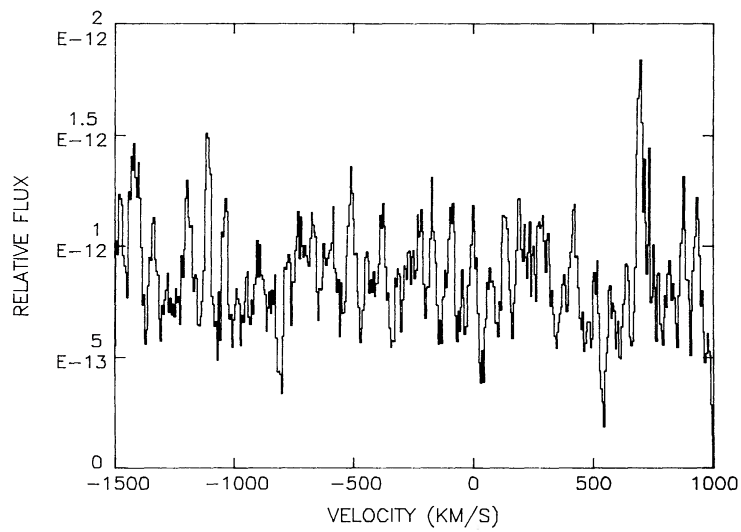

FIG. 1*b*

FIG. 1.—(*a*) A plot of relative flux vs. velocity in the region of Si IV λλ1393, 1402 for SWP 32659H. The separate components of this resonance doublet have been co-added on a common velocity scale. The data have been five-point smoothed. (*b*) The same as (*a*) except for C IV λλ1548, 1550.

that orbital velocity smearing of features was minimal. In Figure 2 the separate Si IV and C IV plots of Figure 1*a* and 1*b* have been co-added.

Our identifiable line detections fall into three categories: (1) interstellar absorption in the line of sight to the Hyades cluster; (2) broad stellar wind features; (3) narrow, high-velocity circumbinary absorption independent of orbital phase. We discuss these three categories in turn before turning to a discussion of our search for white dwarf photospheric features.

3.2.1. *Interstellar Absorption Lines*

In all of the eight images in Table 1, weak interstellar lines appear at a slight redshift (+7 to +20 km s^{-1}), consistent with other studies of the line of sight to the Hyades (e.g. Murthy et al. 1989). These were low-ionization species (C II, Si II, O I, N I) with implied column densities consistent with a rather low density substrate of the local interstellar medium in that direction. A typical interstellar line is shown in the velocity co-addition plot of C II, Si II, and O I displayed in Figure 3 for SWP 15900. In one noisy image (SWP 28826) the same co-added plot was devoid of the interstellar lines but otherwise the interstellar velocities repeated from image to image as expected.

3.2.2. *Absorption due to Wind from K2 Dwarf*

In several images we detected broad absorptions which can readily be identified as arising in the recently discovered wind outflow emanating from the K2V star (Mullan et al. 1989). An example of this can be seen in Figure 3 (SWP 15900) where the broad feature at velocity −260 km s^{-1} is the wind absorption in C II + Si II + O I, first noted by Bruhweiler & Sion (1986). These episodic wind features are also displayed in Figure 4 where the same cool ions have been co-added for SWP 32659. Here the broad phase-dependent wind component shows up clearly at −450 km s^{-1} consistent with the same preferred velocities noted by Mullan et al. (1989) in the 11 LWP high-resolution spectra in the regions of Fe II and Mg II *h* and *k*.

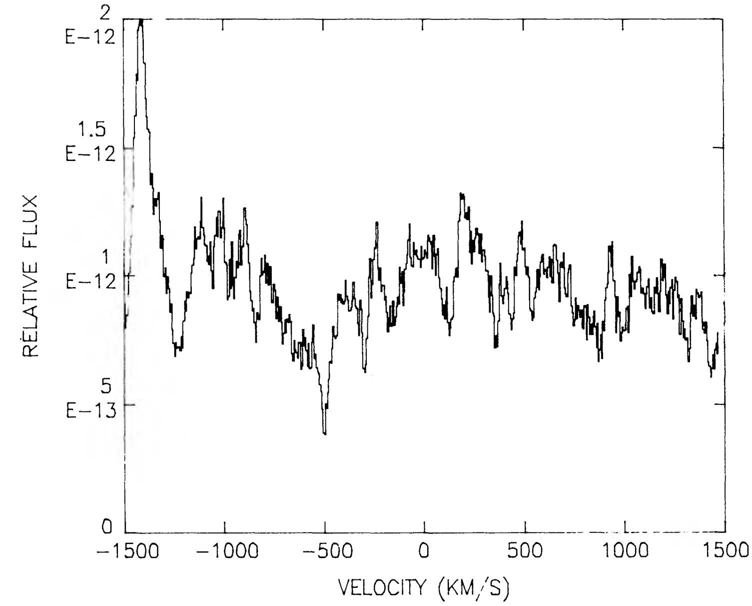

FIG. 2.—The same as Figs. 1*a* and 1*b* except with the components of Si IV and C IV in Fig. 1*a* and 1*b* co-added on a common velocity scale

3.2.3. *Circumbinary Lines*

Strong evidence of cool, very narrow, high-velocity circumbinary absorption at -1200 km s^{-1} (Sion et al. 1989) and at -590 km s^{-1} (Bruhweiler & Sion 1986) is present in those SWP images with the best signal to noise, an example of which is displayed in Figure 5 for SWP 15898. These features show up more strongly in the LWP images at the Fe II UV1 multiplet and in Mg II, as discussed by Sion et al. (1989). Both features may be associated with nova-like mass ejection events associated with the white dwarf.

Also present in Figures 4, 5, and 6 are redshifted feature, longward-shifted by 0.5 to 0.9 Å, corresponding to orbital velocities of between 117 and 250 km s^{-1}. These appear to be interstellar features (e.g., C II λ1334 relative to C II λ1335), artificially displaced in the co-addition process, since not all interstellar lines in each of the three regions (O I + C II + Si II) were co-added on a common velocity scale. However, the possibility of a contribution to this feature by longward-shifted (circumbinary?) absorption cannot be ruled out. These features are too strong to originate on the surface of a white dwarf with effective temperature of 35,000 K.

3.3. *White Dwarf Photospheric Features?*

We have carefully examined all eight *IUE* spectra in the velocity windows corresponding to the white dwarf photosphere. *We can find no definitive evidence for any real absorption features in the strong resonance doublets of* C IV, Si IV, *or* N V. We estimate that the upper limits on the absorption features in either Si IV or C IV is ~50 mÅ.

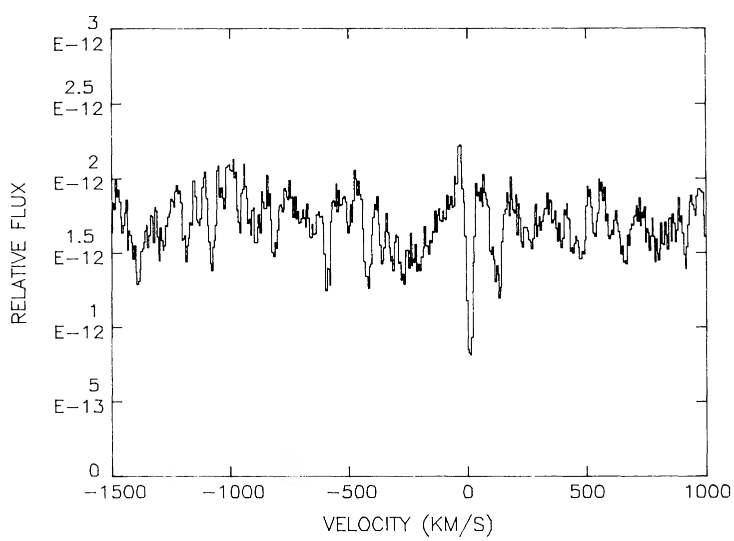

FIG. 3.—A plot of relative flux vs. velocity plot showing O I λ1302, C II λ1335, and Si II λ1260, co-added on a common velocity scale for SWP 15900H. Note the interstellar absorption feature slightly redshifted in the direction of the Hyades. The broad absorption trough centered at -260 km s^{-1} is due to the K2V star's stellar wind absorbing white dwarf continuum (see text).

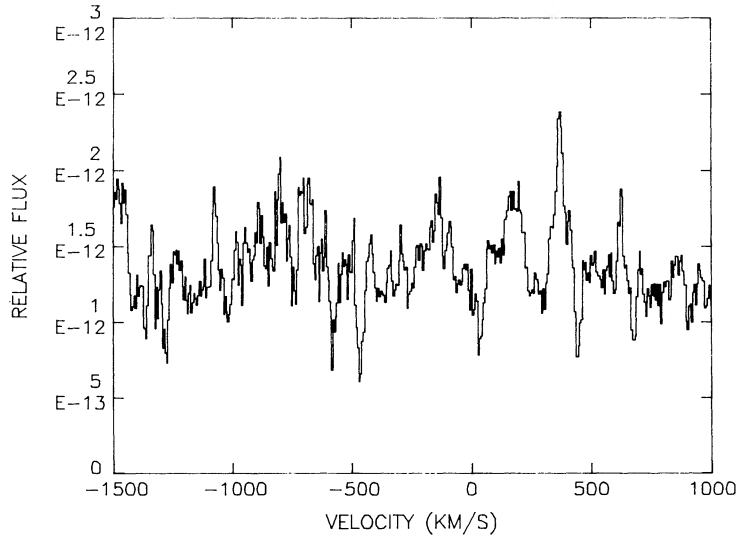

FIG. 4.—The same ions as in Fig. 3 except for SWP 32659H. The two absorption features near −500 km s^{-1} are real. The feature at −575 km s^{-1} is circumbinary gas (Bruhweiler & Sion 1986) and the broader feature at −450 is due to orbital phase-dependent absorption by the wind from the K2 dwarf (Mullan et al. 1989).

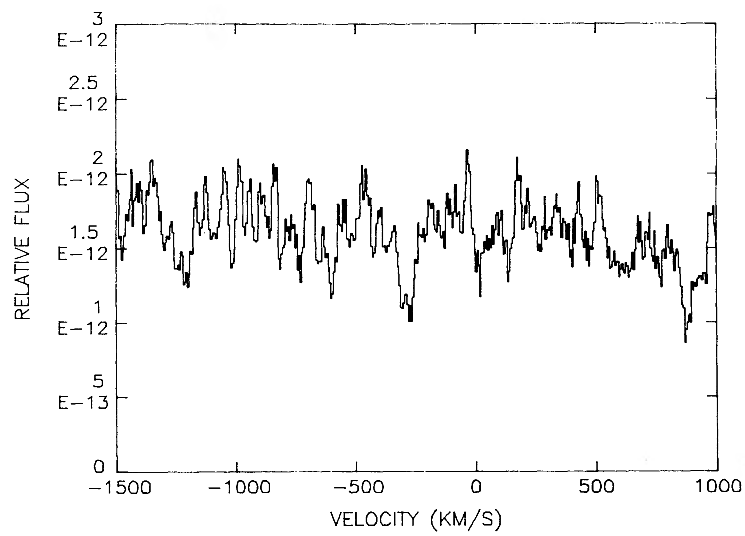

FIG. 5.—The same ions as in Fig. 3 except for SWP 15898H. The absorption feature at −250 km s^{-1} is due to the K2V stellar wind while the absorption features at −575 and −1200 km s^{-1} have been identified as circumbinary (see Bruhweiler & Sion 1986 and Mullan et al. 1989, respectively).

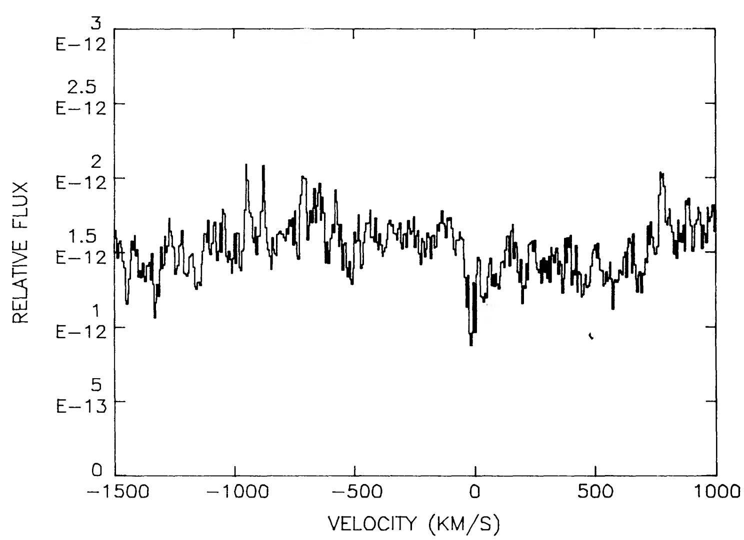

FIG. 6.—The same ions as in Fig. 3 except for SWP 32649H

For example, the Si IV spectrum shown in Figure 1*a* (SWP 32659) was obtained at phase 0.75 (Table 1). As was discussed above, at phase 0.75, the velocity window in which we should search for white dwarf photospheric features extends in the most extreme case from +220 to +260 km s^{-1}. Within this range in Figure 1*a*, we see that the most prominent absorption feature is centered at +240 km s^{-1} and has a full width of no more than 20–30 km s^{-1} (i.e., no more than 0.14 Å in wavelength). Even with the most generous possible placing of the continuum level (at the highest "spike" in the window), the central depth of this most prominent feature is no more than 0.5. Hence, an equivalent width of 0.035 Å (assuming a triangular profile) is certainly a very generous upper limit on any white dwarf photospheric feature in Figure 1*a*. For future reference, we note that other lines can be identified in the spectra which seem to have central depths less than 0.5, perhaps as small as 0.1–0.3.

In Figure 1*b*, where the C IV spectrum is shown for the same spectrum as in Figure 1*a*, examination of the velocity window from +220 to +260 km s^{-1} reveals a maximally strong feature of full width 0.2 Å, and maximum central depth no more than 0.5 (even with generous placement of the continuum). Thus, with a triangular profile, an equivalent width of 0.05 Å is certainly a generous upper limit.

Moreover, a cursory inspection of Figure 1*a* and 1*b* shows that the features which we have considered as the "maximal" features in our velocity window actually appear little different from almost every other "feature" in the figure. This suggests that the "features" may in fact be merely noise. Thus, the true white dwarf features in our spectra (if there are any such features) probably have equivalent widths even smaller than the generous upper limits of 50 mÅ mentioned above.

To interpret these limits in terms of abundances, we refer to simulations of white dwarf spectra obtained by Henry, Shipman, & Wesemael (1984). These authors found that if the photosphere of a 35,000 K DA star contains material with solar composition (Si/H = 3×10^{-5}; C/H = 3.5×10^{-4}), the spectrum should show Si IV and C IV features with equivalent widths of $\sim$2500 mÅ and 1200 mÅ, respectively. (These figures can be obtained from Tables 10 and 5, respectively, in Henry et al., by interpolating linearly between effective temperatures of 30,000 and 40,000 K.) The complete absence of N V in absorption, or of Einstein-redshifted He II λ1640 in absorption in any of the spectra in Table 1 is less puzzling because of the higher temperatures required.

We can use the model calculations of Henry et al. (1984) to set upper limits on carbon and silicon abundances from the non-appearance of photospheric features above our detection limit of $\sim$50 mÅ. From Tables 10 and 5 of Henry et al. we find that the implied upper limits on the abundances are Si/H $< 1 \times 10^{-8}$ and C/H $< 1 \times 10^{-7}$. By comparison with the solar abundances of silicon and carbon relative to hydrogen, our results suggest that *the* Si *and* C *abundances at the photosphere of the white dwarf in V471 Tauri are at least 3.5 orders of magnitude smaller than solar.*

The above estimates are valid only if the Si and C are distributed uniformly over the surface of the white dwarf. If instead, the Si and C are confined to certain areas (such as magnetic polar caps), our conclusions would be altered. For example, if the polar caps occupied only 10% of the surface area, then our upper limits on Si IV and C IV line strengths imply that Si and C abundances in those caps are at least 2.5 orders of magnitude smaller than solar. In even smaller caps, the abundances of Si and C would be larger. However, in order to have the Si and C abundances in the caps as large as the solar values, the areas of those caps would have to be smaller than 0.03% of the surface area: although we cannot exclude the latter possibility, it would seem to require a remarkable focusing of accreted material. (See further discussion in §§ 4.2 and 4.5 below.)

Our quantitative conclusions on Si and C abundances may be affected somewhat if the white dwarf is rotating rapidly. We discuss this in § 4.2 below.

4. DOES THE DA2 WHITE DWARF ACCRETE FROM ITS K2V COMPANION?

We appear to be faced with a dilemma. On the one hand, the detection of a cool wind emanating from the K2V star by Mullan et al. (1989), as well as the documented occurrence of large flares on the chromospherically active K2V star (see, e.g., DeCampli & Baliunas 1983; Young et al. 1983), both suggest that the white dwarf in the system must find itself immersed in a relatively heavy flow of material. In this situation, accretion onto the white dwarf would seem to be almost inevitable. On the other hand, the apparent absence in all of our *IUE* spectra of photospheric metal features or helium suggests that accretion, if it is occurring at all, must be quite inefficient. The purpose of this section is to examine possible resolutions of this dilemma.

4.1. *Estimate of Nominally Expected Accretion Rate onto White Dwarf*

The accretion of material onto a star is a complicated process involving many factors. These include the nature of the incoming flow (Is it fluid-like or can the particles be treated as noninteracting? The answer depends on the collisional cross sections of the constituent atoms), the ionization state of the incoming gas (How is it affected by photoionization due to the white dwarf? Collisional cross sections for ions are much larger than for neutrals), grains in the flow, a wind from the white dwarf, and the presence of magnetic fields and rotation. These have been discussed extensively in the context of accretion of interstellar gas by a white dwarf by Alcock & Illarionov (1980). Here we examine the problem in the context of a white dwarf located in the much denser medium provided by the K2 star wind.

The simplest approach to accretion of a passing wind by a star is provided by the Bondi-Hoyle treatment (1944). This is an appropriate treatment if the incoming gas behaves as a fluid (Alcock & Illarinov 1980): we will check this below. The characteristic impact parameter for the K2V wind material to be captured by the white dwarf is simply (in the absence of a magnetic field) the Bondi-Hoyle accretion radius R_a given by

$$R_a = 2GM_{wd}/V_{rel}^2 \quad (1)$$

where

$$V_{rel} = V_w + V_{orb} \quad (2)$$

is the sum of the wind speed and the orbital speed.

For the computations that follow below, we adopt the following parameters for the V471 Tauri system (Young & Lanning [1975]): orbital period 12.5 hr, $M_{wd} = 0.72\ M_\odot$, radius of the white dwarf $r_{wd} = 8.4 \times 10^8$ cm, semimajor axis of white dwarf orbit $a_{wd} = 1.48 r_\odot$, semimajor axis of K2 dwarf orbit $a_{K2} = 1.54 r_\odot$, separation between the K2 dwarf and the white dwarf $D = 2.2 \times 10^{11}$ cm, orbital velocity of white dwarf with respect to K2 dwarf, $V_{orb} = 320$ km s^{-1}. With $V_w = 600$

km s^{-1} (Mullan et al. 1989), the accretion radius is then found to be

$$R_a = 2.3 \times 10^{10} \text{ cm} . \quad (3)$$

If the flow can be treated in the fluid approximation, the amount of wind material gravitationally captured by the white dwarf is given by

$$\dot{M}(\text{acc}) = (\pi R_a^2/4\pi D^2)\dot{M}(\text{wind}) . \quad (4)$$

Here, $\dot{M}$(wind) is the mass loss rate from the K2 dwarf.

The criterion for fluid flow (Alcock & Illarionov 1980) is

$$T_{\text{AI}} = n_\infty \sigma R_a \gg 1 . \quad (5)$$

Here n_∞ is the density of the accreting material at infinity, and σ is a collision cross section. The density of the K2 star wind at the surface of the white dwarf, $\rho(D)$, is estimated below (eq. [16]) to be (4–8) $\times 10^{-17}$ g cm^{-3}. This can be taken as a measure of n_∞, which then has the value (3–5) $\times 10^7$ cm^{-3}. Using equation (9b) from Alcock & Illarionov (1980), we find that T_{AI} exceeds unity as long as σ exceeds 1×10^{-18} cm^2. This is certainly satisfied for collisions involving hydrogen atoms and ions. (Elastic collisions between ions and neutrals in the energy range of interest to us here, ~100 eV, have cross sections which are comparable to geometric cross sections of the atoms, i.e., of order 10^{-16} cm^2; see Mott & Massey 1933.) Thus, it appears that the fluid approximation in our case is satisfactory.

Using, therefore, the Bondi-Hoyle formulas, and with $\dot{M}$(wind) = (2–4) $\times 10^{-11}$ $M_\odot$ yr^{-1} (Mullan et al. 1989), we predict that the white dwarf should be accreting at the rate

$$\dot{M}(\text{acc}) = (0.6\text{–}1.2) \times 10^{-13} M_\odot/\text{yr} . \quad (6)$$

The white dwarf may have been accreting at the above rate since it emerged from the common envelope phase of evolution. How long ago did that happen? It cannot be less than the cooling time of the white dwarf $\tau_{\text{cool}} = 2.5 \times 10^7$ yr, but it may be much longer: since V471 Tauri is a member of the Hyades (Young & Nelson 1972), the K2 dwarf in the system may be as old as 10^9 yr, and we may be seeing the white dwarf in the aftermath of one or more thermal runaways. Thus, with the above accretion rate, the white dwarf may have accreted a hydrogen layer with a mass of at least 3×10^{-6} $M_\odot$ and perhaps as large as 1.2×10^{-4} $M_\odot$. This range of masses is potentially interesting because it includes (marginally) the possibility of the white dwarf having undergone a thermonuclear runaway with mass ejection. Using estimates given in earlier work (MacDonald 1983), we estimate that a white dwarf with mass 0.72 $M_\odot$ (such as in V471 Tauri) must accrete a mass of ~2×10^{-4} $M_\odot$ in order to drive the star to have a strong enough thermonuclear runaway to eject a significant shell of matter. This critical mass is only slightly larger than the upper limit estimated above for V471 Tauri. The discovery of cool expanding gas in the line of sight to this system (Bruhweiler & Sion 1986; Sion et al. 1989) may indicate that a nova-like mass ejection event has in fact occurred sometime in the past.

However, the major question we address here is: *if the white dwarf is in fact accreting at the rate given by equation* (6), *why is there no direct spectroscopic evidence of photospheric accretion in either low-resolution or high-resolution IUE spectra where the white dwarf dominates the light virtually uncontaminated by the K2 star?*

Several possible answers are explored here: (1) smearing out of the lines by rapid rotation of the white dwarf; (2) downward diffusion of accreted heavy elements at a rate faster than wind accretion can resupply them; (3) prevention of accretion by a white dwarf wind which might form a stand-off shock in the K2 star wind; and (4) rotation of a magnetosphere attached to the white dwarf preventing accretion in detectable amounts via a "propeller" mechanism. As a final case, we consider (5) the possibility of neutrals in the incoming wind. We examine these in turn.

4.2. *Smearing Out of Spectral Features due to Rapid Rotation of the White Dwarf?*

It might be argued that C IV and Si IV features are indeed present in our spectra with the strengths predicted by Henry et al. (1984), but rotational broadening has reduced their central depth to such small values that the lines are lost in the noise. To assess this effect, we need to know the rotational velocity of the white dwarf, v_{rot}. There is no direct evidence as to the value of v_{rot}. Two extremes come to mind: the white dwarf may be rotating much faster than the orbital period, or the two periods may be synchronized. (A quantitative discussion of how the system might evolve from one of these extremes to the other can be found in Lamb & Melia 1987.) At the slow extreme, with the white dwarf in enforced synchronism with the orbit, v_{rot} is miniscule, of order 1 km s^{-1}: this is so small compared with the *IUE* resolution (15 km s^{-1} pixel^{-1}) that it would cause no detectable smearing. At the other extreme, let us suppose, for the sake of argument, that the 9.25 minute periodicity (Jensen et al. 1986) is rotational in origin: then $v_{\text{rot}} \approx 90$ km s^{-1}. Rotation of such a magnitude would smear out photospheric features over some 10 *IUE* pixels (~0.8A FWHM in wavelength) if the material absorbing the feature were spread uniformly over the surface. The equivalent widths of the lines would not be altered.

How would this smearing affect the central depths of lines? To answer this, we refer to work of Jensen, Shipman & Sion (1991). These authors have simulated absorption line spectra using white dwarf model atmospheres with $T_{\text{eff}} = 35{,}000$ K and various abundances of trace elements confined to two "spots" on the surface. The "spots" are meant to simulate two magnetic polar accretion regions. The spots are assigned a total area of 11% of the white dwarf surface, both are located on the spin equator of the white dwarf and are separated in longitude by 163°. The white dwarf is assumed to rotate at 9.25 minutes. (Spot sizes and locations are chosen so as to fit best the *EXOSAT* X-ray curve.) By placing the "spots" on the equator, the rotational smearing of the line profile is forced to have a maximum effect. With these parameters, if Si/H is chosen to have a value of 0.01 times solar in the "spots" (and zero elsewhere), a spectrum with resolution similar to that of our *IUE* spectra (~20 km s^{-1}) is found to create a Si IV resonance line with equivalent width 0.06 Å, a full width of ~ 120 km s^{-1} (0.6 Å), and a central depth of 0.3. (All these values are averaged over the 9.25 minute period, in order to make comparisons with our *IUE* spectra: the latter all have exposures which are many times longer than 9.25 minutes.) Note that the confinement of silicon to small almost antipodal polar caps which are not both fully in view at any one instant means that the full width of the line is not quite as broad as if the entire surface were covered with silicon.

Would we have detected such broad, rather shallow lines in our *IUE* spectra? As remarked above, central depths of 0.1–0.5 are detectable in our spectra. Hence, although rotational smearing causes the central depths to be reduced to 0.3, such lines would have been detectable in our spectra.

However, if the white dwarf is indeed rotating as rapidly as 90 km s^{-1}, the predicted full widths of the lines (120 km s^{-1}, i.e., ~0.6 Å) would mean that narrow features (with widths of 0.1–0.2 Å), which we discussed above when we were attempting to extract upper limits on Si IV and C IV equivalent widths are certainly due to noise and cannot be relied upon to provide quantitative information on abundances in the white dwarf photosphere. Instead, in order to place the most conservative upper limits on the strength of photospheric features, we need to expand the velocity window in which we search by ± 60 km s^{-1}, and integrate over all features in that broadened window. For example, in Figure 1*a*, rather than searching from +220 to +260 km s^{-1} and picking out only the strongest feature, we now need to integrate over all features between +160 to +320 km s^{-1}. In Figure 1*a*, setting the continuum level at a relative flux of 1.1×10^{-12}, we find that the entire absorption integrated over the above velocity range has an equivalent width of somewhat less than 0.1 Å. In Figure 1*b*, setting the continuum level at a relative flux of 1.0×10^{-12}, we find that the absorption between +160 and +320 km s^{-1} has an equivalent width of ~0.12 Å. In both cases, these estimates are about a factor of 2 larger than the limits of 0.05 Å estimated above. Thus, even with the very generous choice of velocity window described here, the most conservative estimates of the equivalent widths of Si IV and C IV in the white dwarf in V471 Tauri are still smaller than those predicted by Henry et al. (1984) (for solar abundances) by factors of at least 10. Referring to Tables 10 and 5 of Henry et al. (1984), we find that even with the larger values of equivalent width estimated here, the abundances of Si/H and C/H are still required to be less than solar by a large amount (at least 2.5 orders of magnitude). Note that in the ranges of equivalent widths we are discussing here, the lines are on the flat part of the curve of growth where a factor of 2–3 in equivalent width corresponds to about one order of magnitude in abundance. Of course, if the Si and C are confined to polar caps, then our conclusions will be modified as above. However, even with the larger upper limits estimated here, the Si/H and C/H abundances in the putative polar caps could be as large as solar only if those caps occupy only 0.3% of the total area of the star. This would still require a very high degree of focusing of the accreted material.

Thus, we conclude that even with a rather extreme assumption about the rotational period of the white dwarf in V471 Tauri, we can still set quite stringent upper limits on the abundances of Si/H and C/H in the white dwarf photosphere. Therefore, rapid rotation of the white dwarf cannot be called upon to "hide" the presence of material which has truly solar abundances. A further reason for this conclusion will be discussed below in connection with the "propeller" mechanism.

4.3. *Downward Diffusion of Heavy Accreted Elements Faster than Accretion Resupplies Them?*

The observations of V471 Tauri demonstrate that the photosphere of this object is predominantly hydrogen down to a depth of 0.1 g cm^{-2}, where depths are expressed as mass loading *m*:

$$m = \int \rho \, dx . \quad (7)$$

The X-rays from the white dwarf are identified as thermal X-rays which emerge from deep in the photosphere, from photospheric layers which are considerably deeper and hotter than the layers producing optical radiation (Jensen et al. 1986). The observations cited above also show that the carbon abundance is considerably less than the solar value at layers above UV optical depth unity: the latter occurs at

$$m(\tau_{UV} = 1) = 3 \times 10^{-2} \text{ g cm}^{-2} . \quad (8)$$

For $T_{eff} \approx 35{,}000$ K (as for the white dwarf in V471 Tauri), there is no convection zone in a white dwarf composed of pure hydrogen. Thus a consideration of the balance between accretion and diffusion is quite simple if the accretion is spherically symmetric. Using our estimate given above for the accretion rate onto the white dwarf, (eq. [6]), and spreading it out uniformly over the surface area of the white dwarf, we can express the accretion rate in terms of the mass loading which would be accreted each year: the result is $30 \times \dot{M}_{13}(\text{acc})$ g cm^{-2} yr^{-1} where $\dot{M}_{13}(\text{acc}) \equiv \dot{M}(\text{acc})/(10^{-13} M_\odot \text{ yr}^{-1})$ is the normalized accretion rate onto the white dwarf. At this rate, the accreted material will accumulate a mass loading equal to $m(\tau_{UV} = 1)$ in a time interval of

$$\tau_{acc}(\tau_{UV} = 1) = 10^{-3}/\dot{M}_{13}(\text{acc}) \text{ yr} . \quad (9)$$

While diffusion time scales have been calculated by a number of authors, most of the published articles list data at the base of the convection zone. For our purposes here, we seek to know the conditions at the photosphere. Vauclair, Vauclair, & Greenstein (1979) display the diffusion time scale at a variety of depths; at the photosphere their results indicate that the diffusion time scale τ_{diff} is ≈ 3 yr. If diffusion is to remove C and Si from the photosphere of the white dwarf relative to hydrogen in V471 Tauri, then τ_{diff}, the diffusion time scale for C and Si, must be short compared to $\tau_{acc}(\tau_{UV} = 1)$, the time needed to accrete one optical depth's worth of material. It seems highly likely that the chemical abundances of the wind from the K2 dwarf are approximately solar. However, our abundance limits indicate that in the white dwarf, the photospheric abundance of carbon relative to hydrogen is lower than the solar value by at least 2.5–3.5 orders of magnitude: this suggests that at least 6–9 *e*-foldings have occurred in the diffusion of carbon relative to hydrogen. Hence we can quantify the inequality between τ_{diff} and $\tau_{acc}(\tau_{UV} = 1)$ as follows:

$$\tau_{diff} < (0.11\text{–}0.16)\tau_{acc}(\tau_{UV} = 1) . \quad (10)$$

Using $\tau_{diff} \approx 3$ yr, this requires $\tau_{acc} > \approx 18$–27 yr. Combining this with equation (9), this leads us to conclude that

$$\dot{M}_{13}(\text{acc}) < \approx 3 \times 10^{-5} . \quad (11)$$

In other words, matter is accreting onto the white dwarf at a rate of $3 \times 10^{-18} M_\odot \text{ yr}^{-1}$. *This accretion rate must be regarded as remarkably small: it is some* 3×10^4 *times smaller than the Bondi-Hoyle prediction in equation* (*6*) *above.*

It is likely that accretion will be episodic, since activity on the K dwarf is episodic. As a result, the above upper limit for $\dot{M}(\text{acc})$ is a time-averaged value. At times when $\dot{M}(\text{acc})$ exceeds the value quoted above, there might be some signs of detectable carbon. And yet, in our data, which are distributed over a time span of several years, we have found no evidence whatever for carbon.

The discussion in this section is subject to the critical assumption that the accreted material is spread out uniformly over the surface of the white dwarf and is also subject to the uncertainties of diffusion theory. The latter may be quite significant. For example, Chayer, Fontaine & Wesemael (1989) have summarized evidence which indicates that the observed abundance patterns of heavy elements in hot white dwarfs cannot be reconciled with current theoretical predictions.

4.4. *A Wind from the White Dwarf?*

The possibility that winds may flow from white dwarfs has been raised by Chayer et al. (1989) in the context of discrepancies between theory and predictions of radiatively levitated metal lines. They note that a mass-loss rate as small as 10^{-21} $M_\odot$ yr^{-1} can "play havoc with the predicted surface abundances in presence of radiative support." Michaud (1987) has argued that the maximum mass-loss rates from white dwarfs may range from 3×10^{-16} to 3×10^{-11} $M_\odot$ yr^{-1}.

If there is a wind from the white dwarf, it may interfere with the accretion of the incoming wind from the K dwarf. There are two possible approaches to considering this wind-wind interaction: one is to consider particle-particle effects, the second is to consider fluid effects.

At the particle-particle level, Alcock & Illarionov (1980) consider the problem of interstellar neutrals accreting onto a white dwarf. They discuss how charge exchange between the ions of the white dwarf wind and incoming interstellar neutrals can halt the inflow of those neutrals: they conclude that a white dwarf mass loss of order 10^{-9} (v_w/5000 km s^{-1}) $M_\odot$ yr^{-1} may be required to halt such accretion. Here v_w is the relative speed of the white dwarf wind and the incoming neutrals. In our case, the incoming matter has a speed of order 1000 km s^{-1}. Therefore, even if the white dwarf wind is very slow, the minimum value of v_w is 1000 km s^{-1}, and so a mass loss rate of 10^{-12} $M_\odot$ yr^{-1} might suffice to halt accretion if all of the accreting matter is neutral hydrogen. Some of the wind from the K2 dwarf is neutral (Mullan et al. 1989), but the temperature of the wind ($\sim$20,000 K) is probably sufficient to ionize most of the hydrogen. Thus, this particular aspect of Alcock & Illarionov's work is probably less applicable to the V471 Tauri case. Moreover, as the K star wind plasma attempts to stream through the white dwarf wind plasma, two-stream interactions are expected to occur: these give rise to coupling between the two winds on length scales which are much shorter than the formal mean free path for ion-atom charge exchanges. Because of this, the particle treatment does not seem applicable in the present case.

A fluid treatment of the wind-wind problem is given by Huang & Weigert (1982). In the presence of a wind from the white dwarf, gas flowing from the K2 dwarf will be stopped above the surface of the white dwarf by a standoff shock if the ram pressure is sufficient (Huang & Weigert 1982). Quantitatively, the K2 wind can be held back if

$$\dot{M}(\text{wd})v_w(\text{wd})/4\pi r(\text{wd})^2 > \dot{M}(\text{K2})v_w(\text{K2})/4\pi D^2 . \qquad (12)$$

To use this, we need to know v_w(wd). If narrow absorption features in white dwarf spectra (Bruhweiler & Kondo 1983) are due to wind expansion, the wind must be quite slow (a few tens of km s^{-1}). Setting $v_w(\text{wd}) = 10$ km s^{-1}, and using the figures give above, we find that the K2 wind can be fended off if $\dot{M}(\text{wd}) > (2\text{–}4) \times 10^{-14}$ $M_\odot$ yr^{-1}. If the wind speed is of order the escape speed, then $v_w(\text{wd}) = 5000$ km s^{-1}, and $\dot{M}$(wd) of only 10^{-16} $M_\odot$ yr^{-1} will suffice to fend off the K star wind. These figures are not inconsistent with the range of mass-loss rates discussed by Michaud (1987).

Unfortunately, the direct detection of a white dwarf wind is difficult (although observations with Hubble Space Telescope may make this possible). Moreover, Alcock & Illarionov (1980) point out that the problem of wind-inhibited accretion is quite complicated. If the white dwarf wind is driven by radiation pressure, then one particular set of constraints apply. On the other hand, if the wind from the white dwarf is driven by thermal pressure gradients, then this wind may actually be switched off entirely in the presence of a sufficiently dense "ambient medium" (Talbot & Newman, 1977), i.e. in the presence of a sufficiently large wind from the K2 dwarf. In the absence of detailed modeling of these processes, we cannot assess whether this mechanism contributes a dominant effect in explaining our results, or is negligible.

4.5. *Magnetic and Centrifugal Inhibition of Accretion by the White Dwarf*

We now consider the possibility that rotation and magnetic fields in the white dwarf play a role in preventing accretion. For this discussion to be meaningful, we must postulate the presence of a magnetic field in the white dwarf in V471 Tauri, despite the fact that no direct evidence exists for such a field.

Given the existence of a magnetic field in the white dwarf, the ram pressure of the K2 wind may be insufficient to penetrate the magnetosphere of the white dwarf. If this occurs, then virtually no material is accreted (Lamb 1989). (There is an analog with the Earth here: the Earth, which has a diameter similar to the white dwarf in V471 Tauri, is also located in the supersonic wind flow from a cool dwarf star, and the Earth's magnetosphere fends off the wind quite effectively.) In the present section, we attempt to quantify this idea by following the discussions of infall onto a rotating magnetic degenerate given by Davidson & Ostriker (1973), Lamb, Pethick, & Pines (1973), Illarionov & Sunyaev (1975), and Stella, White, & Rosner (1986). Note that in these earlier discussions, it is customary to assume that the companion star is overflowing its Roche lobe, and therefore supplying matter to the compact object in great amounts but at very low speeds: here, we consider a different case, where the mass transfer rate is small, but the speed of the flow is highly supersonic.

The application of wind accretion theory to a rotating, magnetized, compact stellar remnant (in our case a DA2 white dwarf) can be considered in terms of three critical radii (see Stella, White, & Rosner 1986): (1) the accretion radius R_a (see equation [1] above); (2) the magnetospheric radius, R_m, defined as the distance at which the magnetic field pressure of the putative magnetic white dwarf balances the ram pressure of the incoming wind; this radius is obtained from the condition

$$B^2(R_m)/8\pi = \rho(R_m)v_w^2 \; ; \qquad (13)$$

and (3) the corotation radius, R_c, at which the white dwarf corotation velocity is equal to the Keplerian velocity; viz.,

$$R_c = (GM_{\text{wd}} P_{\text{wd}}^2/4\pi^2)^{1/3} , \qquad (14)$$

where P_{wd} is the rotation period of the white dwarf.

The ram pressure of the wind from the K2 dwarf when it reaches the neighborhood of the white dwarf can be estimated by assuming a constant rate $\dot{M}$ of spherical outflow with constant wind velocity $v_w = 600$ km s^{-1} (Mullan et al. 1989) at a radial distance of D (the orbital separation) from the K2 dwarf. The density $\rho(D)$ at such a distance is given by

$$\dot{M} = 4\pi D^2 \rho(D) v_w . \qquad (15)$$

Using the parameters cited above, we find that the density of the K star wind when it reaches the neighborhood of the white dwarf is

$$\rho(D) = (4\text{–}8) \times 10^{-17} \text{ g cm}^{-3} . \quad (16)$$

With these values, equation (13) yields a value of 2–4 G as the white dwarf magnetic field strength which has a pressure equal to the ram pressure of the K star wind. Assuming that the magnetic field of the white dwarf is a dipole with polar strength B_6 MG, we find the magnetospheric radius to be

$$R_m/r_{\rm wd} = (60\text{–}80) \times B_6^{1/3} . \quad (17)$$

In dimensional units, the magnetospheric radius is

$$R_m = (5\text{–}6.7) \times 10^{10} \; B_6^{1/3} \text{ cm} . \quad (18)$$

This is the radial distance at which the K star wind will be halted in the magnetic equatorial plane. If the inequality $R_m > R_a$ is satisfied in V471 Tauri, the magnetic field of the white dwarf halts the inflow at such great distances that the halted material experiences very little gravitational attraction to the white dwarf. As a result, the Bondi-Hoyle gasdynamic accretion is significantly inhibited, and the accretion rate must fall below what equation (6) predicts. Comparing equations (18) and (3), we see that $R_m > R_a$ if

$$B_6 > 0.04\text{–}0.1 . \quad (19)$$

This leads us to the conclusion that *if the white dwarf in V471 Tauri has a polar field in excess of* 40–100 kG, *the magnetosphere inhibits accretion of wind from the K2 dwarf.*

Note that if the white dwarf is losing mass (§ 4.4 above), the field strengths required to withstand the ram pressure of the K2 star wind would be reduced below the above estimates.

Fields of the above magnitude have been searched for in a few field white dwarf stars (Angel & Landstreet 1970; Preston 1970; Trimble & Greenstein 1972; Elias & Greenstein 1974). These searches were made some time ago using Balmer lines. The less sensitive search technique was to search for net polarization in the lines because the differently circularly polarized components of the Balmer lines are displaced in different directions. Schmidt (1989) indicates that fields in the range $10^{5\text{-}6}$ G should in principle be detectable by shifts of high-order Balmer lines due to quadratic Zeeman effect: hence, fields at the upper end of our estimated range might be marginally detectable. For V471 Tauri, observational determination of magnetic field strengths may become possible if spectra can be obtained in the range 900–1200 Å. In the next decade or so, instruments such as FUSE/Lyman and the ASTRO Space Shuttle payload may provide these data. If the Lyman lines have sharp non–LTE cores like those analyzed by Pilachowski & Milkey (1987), then high-resolution observations of the Lyman line cores could detect the π and σ components of the Lyman lines, if they are indeed separated by a magnetic field. Circular polarimentry in this spectral region could, following their technique described by Elias & Greenstein, detect fields of a hundred kilogauss or so in V471 Tauri.

At present, there is no direct evidence to indicate that the polar field in the V471 Tauri white dwarf does in fact exceed 40–100 kG. Hence we cannot at present assert reliably that the white dwarf is inhibited from accreting wind material from the K2 dwarf by a purely magnetic process.

In view of the above uncertainties in estimating the field strengths in V471 Tauri, we need to examine the possibility that the field is weaker than 40–100 kG. In such a case, R_m becomes less than R_a and the wind will penetrate beneath the accretion radius before being stopped by the field. If the magnetic axis is parallel to the orbital axis, incoming wind will thread field lines at R_m and will be accreted onto the surface of the white dwarf only at the footpoints of those field lines. If the magnetic axis is inclined to the orbital axis, the incoming wind may penetrate somewhat deeper into the magnetosphere before being frozen onto certain field lines. In any case, the incoming wind has access to the white dwarf surface only at the footpoints of certain field lines: the farther away the wind can be halted, the smaller will be the area of the polar cap where material eventually can settle onto the white dwarf surface.

Indeed, such nonspherical accretion is critical to one possible explanation of the X-ray modulation discussed by Jensen et al. (1986). A consideration of the consistency of the dark pole model for X-ray modulation with the data presented here goes beyond the scope of the present paper: it is the topic of a forthcoming paper by Jensen, Shipman, & Sion (1991). Briefly, the chemical composition of the X-ray absorbers, as well as the fraction of the stellar surface covered by material opaque to X-rays, are free parameters which can be adjusted to determine whether any particular dark pole model fits within the observational constraint determined here, namely, that there are no C IV or Si IV features stronger than 50 mÅ when averaged over the entire visible stellar disk.

However, we need to consider the possibility that the rotation of the white dwarf might also inhibit accretion by the so-called "propeller" mechanism (Illarionov & Sunyaev 1975). This mechanism occurs if the corotation radius R_c turns out to be smaller than R_m (Stella et al. 1986): in such a case, when the accreting wind is halted at R_m, some of the halted material may gain access to the interior field lines (closer to the white dwarf) and thereby be forced to corotate with the field but the enforced rotation velocity exceeds the Keplerian velocity at that radius, and so the material tends to be flung out of the gravitational well of the white dwarf.

To evaluate the propeller mechanism in V471 Tauri, we need to know the rotation period and also the time scale required for incoming material to gain access to the fast-rotating inner field lines. Unfortunately, the white dwarf rotation period is currently unknown. For purposes of estimating R_c, we may use three possible values which probably span the entire permissible range of periods: (*a*) $P_{\rm wd} = 9.25$ minutes if the observed X-ray/optical periodicity (Jensen et al. 1986, Robinson et al. 1988) is due to rotation; (*b*) the white dwarf has a rotational velocity corresponding to the upper limit $v \sin i$ of single degenerates, namely 65 km s^{-1} (Pilachowski & Milkey 1985), in which case $P_{\rm wd} = 700$ sec (although admittedly the rotational velocity of a white dwarf in a close binary such as V471 Tauri may have little to do with the rotational velocity distribution of single degenerates); and (*c*) the white dwarf rotation is synchronous with its orbital period, i.e., $P_{\rm wd} = 12.5$ hr. These three cases yield corotation radii of

$$R_c = (a)\; 0.9 \times 10^{10} \text{ cm}; \quad (b)\; 1.1 \times 10^{10} \text{ cm}; \quad (c)\; 17 \times 10^{10} \text{ cm} , \quad (20)$$

respectively. Comparing equation (20) with equation (18), we see that the first two values of R_c satisfy the propeller requirement ($R_c < R_m$) for all polar magnetic fields of the white dwarf in excess of 2–6 kG. Fields in excess of such low limits seem quite likely in a white dwarf. Therefore, *if the white dwarf in V471 Tauri rotates in a period of* 700 s *or shorter, it is likely that the propeller mechanism will prevent the white dwarf from accreting material from the K2 dwarf wind.*

Note that if the white dwarf is indeed rotating as fast as cases *a* or *b*, rotational broadening of spectral lines would be significant: it was mentioned above (§ 4.2) that this was one possible reason why absorption lines due to accreted material might not have been detected in the spectra. Now we see that we can no longer use this excuse to "hide" the accreted material: if the star is rotating fast enough to "hide" spectral lines, it is also rotating fast enough to drive the "propeller mechanism" and cause rotational inhibition of accretion.

In case *c*, the rotation is so slow that R_c exceeds R_m unless the white dwarf is highly magnetic (with polar field strengths in excess of 40 MG). Although we cannot rule out the existence of such strong fields in V471 Tauri, they seem unlikely: such strong fields should be "easily recognized" (Schmidt 1989) since Balmer lines are present in the spectrum of V471 Tauri, and are characteristically split in fields of more than 10 MG. In the absence of such fields, the propeller mechanism would not be effective in V471 Tauri: in this case prevention of accretion would have to depend solely on magnetic inhibition (as estimated above). Hence, if the white dwarf in V471 Tauri rotates as slowly as once every 12.5 hr, the lack of accreted material in the *IUE* spectra requires that the magnetic field at the poles of the white dwarf exceeds 40–100 kG. As before, these are upper limits if the white dwarf is in fact losing mass.

Finally, in the context of magnetic effects, we should also recall a process which occurs at the interaction region between the solar wind and the Earth's magnetosphere: reconnection. The so-called "flux transfer events" on the dayside magnetopause are believed to occur when the magnetized solar wind undergoes reconnection with the Earth's field, thereby allowing access of solar wind material into the dayside magnetosphere. This is not usually a steady state process, but is "patchy" as if conditions of just the right sort need to be met in order for the process to occur (Russell 1984). The wind from the K2 dwarf in V471 Tauri is very likely to be magnetized since dynamo action in the K2 dwarf is probably strong (Mullan et al. 1989). Hence, when the wind arrives at the white dwarf, the probability that material will be able to penetrate toward the white dwarf may depend sensitively on how efficient reconnection actually is. The reconnection events may ultimately control the time scale required for incoming wind to gain access to the fast rotating magnetic field lines in the inner magnetosphere of the white dwarf.

In summary, we have determined that centrifugal/magnetic inhibition (CMI) of accretion is a possible mechanism for explaining the absence of accreted material in the photosphere of the white dwarf in V471 Tauri. However, we have not estimated quantitatively the degree of inhibition which CMI provides. For example, some accretion is still likely if the incoming wind can reach the vicinity of the rotation axis of the white dwarf. And the question of the areas of the polar caps in which such accretion might be occurring has not been answered quantitatively. In particular, we cannot yet say whether or not CMI is efficient enough to explain our discovery that the Si/H and C/H abundances in the white dwarf photosphere are 3.5 orders of magnitude smaller than solar. Clearly, a full understanding of the magnetic and rotational inhibition of accretion in V471 Tauri requires more detailed quantitative considerations which are beyond the scope of the present paper.

4.6. *Accretion of Neutral Species*

The presence of neutrals in the accreting flow may have a significant effect on the amount of material accreted (Alcock & Illarionov 1980). In particular, the magnetic/rotational inhibition of accretion operates directly only on ionized species in the wind. Any neutral species which are present will feel the effects of magnetic inhibition only via collisions with the ions. If there is an appreciable neutral component in the K2 dwarf wind, this component will penetrate more deeply toward the white dwarf.

It may seem irrelevant to discuss the presence of neutrals in the wind from a K2 dwarf: after all the corona from which such a wind originates probably has a temperature of 10^6 K or more (Jensen et al. 1986). Nevertheless, the surprising fact that neutral species *do* appear to be present in the wind from the K2 dwarf in V471 Tauri was pointed out by Mullan et al. (1989): some absorption lines due to Mg I in the wind are observed to be comparable in strength to those of Mg II. This led Mullan et al. to the conclusion that the temperature of the wind cannot be much in excess of $(1–2) \times 10^4$ K.

Can the presence of neutral material in the wind from a K dwarf be corroborated? Independent evidence for the existence of neutral matter in the high corona of a K dwarf (AB Dor) has been discussed by Collier Cameron & Robinson (1989, hereafter CCR). Interestingly, AB Dor is a single star which has a rotation period (0.51423 days) almost exactly equal to the orbital period of V471 Tauri: thus, if the K2 dwarf rotation in V471 Tauri is synchronized with the orbit (as seems likely because of its deep convection zone), the dynamo activity might be comparable to that in AB Dor. According to CCR, Hα observations of AB Dor show the existence of neutral hydrogen at distances of several stellar radii above the surface. CCR argue that this cool material is analogous to solar prominences. CCR point out that the neutral hydrogen may eventually escape from the star. If it does, then it would provide an analog of the neutral material which Mullan et al. (1989) have reported in the wind from the K2 dwarf in V471 Tauri.

At temperatures of 2×10^4 K, hydrogen and most of the metals in the K2 dwarf wind will be ionized at least once. However, helium will remain almost entirely neutral. It is possible, therefore, that helium will penetrate closer to the white dwarf in V471 Tauri than other species. Eventually, photons from the 35,000 K photosphere of the white dwarf will ionize the helium. If the helium can penetrate deeply enough into the magnetosphere before photoionization, it may find itself *inside* the corotation radius by the time the magnetic field stops it: in such a case, the propeller mechanism would not operate. In such a case, when the helium would eventually ionize, since it has made its way in relatively close to the white dwarf, it would follow the magnetic field lines down to relatively large polar caps.

To estimate how far a helium neutral will propagate from the K2 dwarf before photoionizing, we note that a hydrogen white dwarf with effective temperature 35,000 K and $\log g = 8$ emits a helium-ionizing energy flux $F(He^+)$ (i.e., at wavelengths $\lambda < 500$ Å) of $\sim 10^{13}$ ergs cm^{-2} s^{-1}. (We have estimated this from the results given by Wesemael et al. 1981 for an LTE unblanketed atmosphere; see their Table 43.) Thus the flux of He-ionizing photons emerging from the white dwarf in V471 Tauri $N(He^+)$ is of order 10^{23} cm^{-2} s^{-1}. At the K2 star surface (some 220 white dwarf radii distant from the white dwarf surface), the ionizing photon flux is $N(He^+, K) \approx 2 \times 10^{18}$ cm^{-2} s^{-1}, and the number density of ionizing photons there is $n(ph) = 7 \times 10^7$ cm^{-3}.

The photoionization cross section $\sigma(He^+)$ at frequencies of 3×10^{16} s^{-1} can be estimated from Lang (1980): it is $\sim 10^{-20}$

cm^{-2}. Therefore, the mean free path of a helium neutral before photoionization near the K2 dwarf surface, $\Lambda = [n(\mathrm{ph})\sigma(\mathrm{He}^+)]^{-1}$ is of order 1.4×10^{12} cm. This is many times greater than the distance to the white dwarf, indicating that the helium may remain neutral during its flight from the K dwarf toward the white dwarf. As the helium approaches the white dwarf, the photon density n(ph) increases as r^{-2}, causing Λ to decrease as r^2. We find that Λ becomes equal to r at $\sim 2 \times 10^{10}$ cm (or $\sim 25 \times r_{\mathrm{wd}}$) from the white dwarf. From these radial distances, therefore, the helium (which has by now accelerated to an infall velocity of almost 2000 km s^{-1}) has a $1/e$ chance of reaching the white dwarf surface in a neutral form. Thus, some of the helium is expected to remain neutral in to radial distances of order 10^{10} cm. Such distances are comparable to our smallest estimates of corotation radii (see above). Helium which becomes ionized at these small radial distances need therefore not to be flung out by the propeller mechanism. Instead the helium will be trapped on the field lines and guided down toward the poles.

This may help us to reconcile the absence of metals in *IUE* spectra with the X-ray "dark" spots proposed by Jensen et al. (1986): the magnetosphere keeps out essentially all metals (because they are at least once ionized), whereas the dark spots may be almost entirely due to accreted helium (a very efficient opacity source in an otherwise pure hydrogen envelope) which has gained deeper access into the magnetosphere by virtue of staying neutral longer. Quantitative modeling of time-dependent ionization of helium will be needed to confirm or refute this hypothesis. And, of course, if it turns out that non-radial pulsations are the source of the X-ray variations, then there may be no need to have "dark" spots on the surface.

5. CONCLUSIONS

The principal observational conclusion of our paper is the following: *in the photosphere of the white dwarf in V471 Tauri, there are no detectable spectral features of carbon or silicon.* The upper limit on the equivalent widths of the resonance lines of C IV and Si IV is ~50 mA.

This result, in view of the known mass outflow from the K2V star, presents a puzzle: although the orbit is a close one, (separation between the K2V star and the white dwarf is only 3–4 K star radii), and the white dwarf is therefore immersed deeply in the wind of the K star, the white dwarf exhibits no evidence for having accreted any of this wind. We estimate that the white dwarf has accreted no more than one part in 3×10^4 of the material which it ought to have accreted if the well-known hydrodynamic considerations of Bondi & Hoyle (1944) are correct. The question is: how does the white dwarf protect itself so effectively from the wind which is flowing past it?

Several possible approaches to resolving this puzzle have been explored in this paper. First is the possibility that the puzzle is not a real one at all, but is only apparent: perhaps the white dwarf is rotating so rapidly that metal lines are indeed present in the spectra but are simply washed out below our detection threshold. We have established that this is almost certainly not the case. For one thing, model spectral lines in the presence of rotation indicate that our observations are capable of detecting the resulting lines of C IV and Si IV. Moreover, if the white dwarf rotates so rapidly as to "hide" absorption lines in *IUE* spectra, the rotation would also be sufficient to inhibit accretion by the propeller mechanism (unless the magnetic field of the white dwarf is weaker than a few kilogauss which seems unlikely).

Second, is it possible that accretion is magnetically inhibited? That is, does the K2V wind have insufficient ram pressure to penetrate the putative magnetosphere of the magnetic white dwarf? We have found that this explanation may be acceptable if the white dwarf has a polar magnetic field strength which exceeds 40–100 kG. No direct measures of the white dwarf field strength exist for V471 Tauri although many white dwarfs are known to have fields stronger than these limits (Schmidt 1989). But even if the fields are not as large as the above limits, a "propeller" mechanism may be at work to eject incoming gas: we estimate that a magnetic field of only 2–6 kG in the white dwarf, combined with a rotation period of order 600 s, will suffice to fend off the incoming wind. Hence magnetic (plus rotational) inhibition of accretion is a possible explanation of the puzzle, although the quantitative details may be very complicated.

Third, is the diffusion time scale of a DA2 star so short that the accreted ions from the accreted wind material sink out of sight at small optical depth, thus evading detection? At the low-accretion regime expected here, this is a possible explanation. However, time scales of a few years are probably required for the sinking. As a result since activity in the K dwarf is episodic (and therefore mass loss rates are also; Mullan et al. 1989), we might expect to have "caught" some accreted material before it had time to sink. Our *IUE* spectra were obtained at intervals ranging from a small fraction of a year to several years. We therefore view this third alternative as a less likely resolution of the puzzle.

Fourth, the white dwarf may have a wind of its own which fends off the incoming K2 star wind in a stand-off shock. We see no way to evaluate this possibility quantitatively at present.

Finally, we point out that if indeed magnetic inhibition of accretion is at work, neutral gas in the wind from the K2 star will not feel the inhibition directly (but only via collisions with ions). Since it has been established that there is indeed neutral material in the K2 star wind (Mullan et al. 1989), we speculate that helium may penetrate more deeply into the white dwarf magnetosphere than other elements. If helium can reach the white dwarf, it will cause significant X-ray opacity effects.

It is a pleasure to express our appreciation to Rosalie Ewald and the staff of the NASA Goddard RDAF for their prompt and competent assistance with data analysis. We gratefully acknowledge support of this work through NASA grant NAG5-343 and NSF grant AST88-02689 to Villanova University, NSF grant AST87-20530 and NASA grant NAG5-972 to the University of Delaware, and NASA Grant NAGW-1295 to Bartol. One of us (H. L. S.) thanks the AAS Shapley Lectureship Program and Lord Fairfax Community College in Middletown, Virginia, for providing the uninterrupted environment in which some of his work on this paper could be completed. We thank K. Jensen for helpful discussions, and an anonymous referee for detailed and incisive comments on a first draft of this paper.

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