EVIDENCE FOR A COOL WIND FROM THE K2 DWARF IN THE DETACHED BINARY V471 TAURI

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ABSTRACT

We report evidence for mass loss from the K2 dwarf in V471 Tauri in the form of discrete absorption features in lines of various elements (Mg, Fe, Cr, Mn) and ionization stages (Mg i, Mg ii; Fe i, Fe ii). Resonant Mg ii absorption indicates a mass loss rate of at least $10^{-11}$ solar masses per year. The wind appears to be cool (no more than a few times $10^4$ K).

Subject headings: stars: binaries — stars: mass loss — stars: winds

I. INTRODUCTION

Mass-loss has hitherto not been detected in cool dwarfs (except the Sun). Typically, strong wind absorption lies in the UV where the continuum is undetectable. V471 Tauri, a detached eclipsing binary [DA2 + K2 V; $P_{\text{orb}} = 12.6$ hr; separation $a = (2-3) R_\odot$]; Jensen et al 1986], may help to circumvent this difficulty: a UV continuum from the white dwarf shines through the putative wind from the K dwarf.

II. IUE OBSERVATIONS

Of 11 IUE echelle images taken at various orbital phases $\phi$, we discuss here only three images at $\phi = 0, 0.5$. During two exposures, the star was stepped across the IUE aperture to compensate for orbital velocity variations during the exposure. See Table 1 for observation log.

During LWP 11476, white dwarf eclipse occupies about one-half of the exposure. In this geometry, a K star wind creates both blueshifted and redshifted absorption. During LWP 11477 and LWP 12448 (white dwarf transiting K star), the K star wind creates only blueshifted absorption, while redshifted absorption indicates accretion onto the white dwarf. LWP 11477 was obtained during the same binary orbit as LWP 11476, whereas LWP 12448 was obtained some 200 orbits later.

Since $P_{\text{orb}} = 12.6$ hr, exposure times are limited, and signal/noise (S/N) ratios in our spectra are not optimal: e.g., using seven-point smoothing in LWP 11476, the mean flux near Mg ii $h$ and $k$ lines is $8 \times 10^{-14}$ cgs, with standard deviation $\sigma = 3.3 \times 10^{-14}$ cgs. In LWP 11477, the figures are $1.2 \times 10^{-13}$ and $3.0 \times 10^{-14}$. Hence, a single dark pixel is a 2–3 $\sigma$ feature in LWP 11476 and a 4 $\sigma$ feature in LWP 11477. Our absorption features are in all cases several pixels wide, and so are quite significant. Nevertheless, to improve S/N, we have co-added (in velocity space) up to seven identified lines from each image. Since IUE camera artifacts may persist (although weakly) even in the co-added spectra, we have been conservative in claiming real features.

III. LINE PROFILES

In Figures 1–3, showing various line profiles, the abscissa denotes velocity relative to an appropriate rest wavelength (e.g., 2795.53 Å for Mg ii lines: on this scale, $h$ line lies at +770 km s$^{-1}$), and the ordinate denotes seven-point smoothed fluxes using standard IUE reductions.

Emissions in Mg ii $k$ and $h$ are prominent (Figs. 1 and 2d), presumably arising in active regions in the K dwarf. (The apparent double peak in $k$ in Fig. 1 is spurious.) K dwarf rotation creates emission widths of almost 200 km s$^{-1}$. More important in the present context are the deep absorption features blueward of Mg ii $k$ (especially Fig. 1). The strongest absorptions in Fig. 1 (essentially black: B1, B2) occur near $-250$ and $-500$ km s$^{-1}$. Noticeable absorption can be seen out to $v_t = -(600-800)$ km s$^{-1}$ depending on where the continuum level lies. Absorption occurs blueward of Mg ii $k$ in all of our spectra, with varying strength depending on the orbital phase. Absorption is also apparent in Figure 1 blueward of Mg ii $h$, although poor image quality makes interpretation difficult.

To confirm the reality of the Mg ii absorption features, we have examined many line profiles in velocity space. Different lines respond differently to radial changes in wind temperature and density, and thus respond differently in velocity space. Ideally, the absorption features should appear most prominently in the strongest lines of the most abundant ion species. However, the absorption features which we seek are spread over 500–700 km s$^{-1}$ in velocity, i.e., over 4–6 Å at 2500–2800 Å. Hence, we require lines with a clean spectrum extending at least 4–6 Å blueward of rest velocity. This is a demanding requirement in the UV spectrum of a K2 dwarf. For example, Fe ii 2599 Å has another Fe ii line (of almost equal strength) at...
−120 km s⁻¹, and a strong line of Mn II at −650 km s⁻¹. Hence, interpretation of 2599 Å is less unambiguous than, say Fe II 2585 Å (a weaker line in the same UV 1 multiplet).

Line profiles are shown in Figure 2 for LWP 11477. Features A, B, C, and D appear in the same velocity range in at least two different lines, although with different relative strengths: e.g., the deepest absorption feature in Fe II 2585 (labeled C in Fig. 2a) extends roughly from −460 to −510 km s⁻¹; the deepest absorptions in both Cr II 2870 and Mn II 2605 (“C” in Fig. 2b) occur also within this velocity range, although in neither case is the absorption trough as wide as in Fe II 2585. Strong absorption between −460 and −500 km s⁻¹ also appears in Mg I 2852 (“C” in Fig. 2c), but this is not the deepest absorption feature in Mg I. Instead, the latter has its deepest feature between −380 and −420 km s⁻¹; counterparts of the latter absorption appear in Mg II 2795 and Cr II 2804. Another prominent absorption feature in Fe II 2585, between −250 and −320 km s⁻¹, has counterparts in Cr II 2870, Mn II 2605, Mg I 2852, and Mg II 2795 (“B” in Figs. 2a–2d). The strongest absorption feature (in terms of equivalent width) in Cr II 2870 occurs at low velocities: this feature has counterparts in Fe II 2585 and Mg I 2852 (see “A” in Figs. 2a and 2c), but not in Mn II 2605.

Certain absorption features appear in two stages of ionization. Thus, in Mg I and Mg II (Figs. 2c and 2d), absorption features B, E, G, I, and flux maxima F, H, J occur with comparable strengths. And strong absorption occurs between 600 and 660 km s⁻¹ in Fe I 2483, Cr II 2870, and Fe II 2585 (“D” in Fig. 2a).

Our search for discrete absorption components in IUE spectra of V471 Tauri extends over more than 1000 Å in wavelength. We have identified some components in wavelengths as short as O I 1302 Å. Over such a range, it is unlikely that the strong absorption features could all be artifacts of the IUE image plate or reduction procedures.

(Absorption features are also apparent on the redward side of various lines in Figs. 1 and 2. These redshifted features will be discussed in a future paper.)

We conclude that the absorption features in our spectra, extending to velocities of 800 km s⁻¹ or more, are real. Since both LWP 11476 and LWP 11477 are velocity-compensated for K dwarf orbital motion, the velocities mentioned here are relative to the K dwarf.

To determine how long the absorption features persist, images LWP 11477 and LWP 12448 were obtained at identical orbital phases (φ = 0.5) but separated by 4 months. Results for co-adding several lines are shown in Figure 3. The prominent absorption features which were discussed above for LWP 11477 are obvious. In LWP 12448, absorption features are readily identifiable at roughly the same velocities: labels A, B, C, and D in Figure 3 correspond to those in Figure 2. However, the features in LWP 12448 are shallower than in LWP 11477, and the widths of the features around −500 and −300 km s⁻¹ have increased by about two. Some of this increase in width may be attributed to the lack of velocity compensation in obtaining LWP 12448. Nevertheless, identifiable structures persist at similar velocities (although with different strengths) of up to about −700 km s⁻¹ over a 4 month interval.

### IV. Discussion

Our spectra suggest that absorbing material exists in V471 Tauri with velocities up to 700–800 km s⁻¹ relative to the K dwarf, i.e., faster than escape speed vₑ from the surface [r = Rₖ(K); vₑ = 600 km s⁻¹]. Since absorption is observed even at phase 0.5 (white dwarf transiting), the absorption features must exist at distances r > a = (2–3)Rₖ(K). Some lower velocity features lie at speeds which exceed the escape velocity from r = (2–3)Rₖ(K) (vₑ = 350 km s⁻¹). This material is therefore escaping from the K star. Since V471 Tauri is detached, we attribute the escaping material to a bona fide wind, rather than Roche lobe overflow. The existence of multiple components, as well as variations from spectrum to spectrum, suggest that the wind is either non-steady or non-spherically symmetric or both.

Applying a curve-of-growth analysis (Spitzer 1978) to Mg II absorption (Fig. 1), we find a firm lower limit on the column density: log N(Mg II) > 14. (The true value will be > 10 times larger, if the turbulent velocity < 100 km s⁻¹.) Since common features can be identified in Mg I and Mg II (see Figs. 2c and 2d), N(Mg I) must equal N(Mg II), roughly. Hence, N(Mg) > 2 × 10¹⁴ cm⁻², corresponding to a total column density of N(H) > 8 × 10¹⁸ cm⁻². In the limit of constant wind

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**TABLE 1**

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<th>Image Number</th>
<th>Year</th>
<th>DOY (UT)</th>
<th>Exposure Time (minutes)</th>
<th>Phase at Midpoint (φ)</th>
<th>Exposure Spread (Δφ)</th>
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<td>20:17</td>
<td>0.521</td>
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velocity, the number density at radius $r$, $n(r)$, corresponds to a column density of $r n(r)$ when integrated along the line of sight from $r$ to infinity. The value of $r$ appropriate for the absorption components is unknown, but with $r = m R_*(K)$ (where $m > 1$), we find $n(r) > 1.3 \times 10^8 m$ cm$^{-3}$. With velocity $= 800$ km s$^{-1}$, the (spherical) mass loss rate is found to be $M > 1.3 m \times 10^{-11} M_{\odot} \text{yr}^{-1}$. With $m = 2$, say, this estimate exceeds the solar rate by $10^3$. The kinetic power in this wind ($L_{KE} = 5 \times 10^{30}$ ergs s$^{-1}$) is $0.0025L_{bol}(K)$, exceeding the coronal radiative power (see Jensen et al. 1986): the K dwarf drives its wind with a high efficiency, some $10^4$ times the solar value (where $L_{KE} = 2 \times 10^{-7} L_{bol}$).

Our Mg spectra have provided a lower limit on $M$. Can we determine an upper limit? In this regard, we note the following:

1. Bondi-Hoyle arguments suggest the white dwarf captures 1% of the K star wind. Now, if the white dwarf in V471 Tauri were to accrete at a rate $> 10^{-13} M_{\odot} \text{yr}^{-1}$, metal absorption features would be detectable in IUE spectra. No such lines have been detected, despite a careful search (Sion 1989).

2. Period variations in pre-cataclysmic variables (of which V471 Tau is one) imply $M$ not greatly in excess of $10^{-11} M_{\odot} \text{yr}^{-1}$ (Hameury et al. 1987).

These arguments indicate upper limits on $M$ from the K dwarf in V471 Tauri which are comparable to our lower limit. Hence, most of the magnesium in the wind from the K star must be in Mg ii, with perhaps comparable amounts in Mg i, but with little or none in the higher stages of ionization. This suggests a temperature which cannot be greatly in excess of $10^4$ K.

In the solar wind, cool material ($T_e < 6 \times 10^4$ K) is associated with coronal mass ejections (CME's) which are magnetically driven: the coolness may be due to closed magnetic topology (Neugebauer 1983). Rapid rotation of the K dwarf in V471 Tauri [$\Omega(K) = 100 \Omega(Sun)$] ensures strong dynamo-
generated fields, perhaps facilitating magnetic driving of mass loss. In contrast to the solar wind, where CME's contribute only a few percent to the mass flux (Hildner 1977), the wind of V471 Tau may be dominated by CME's. Moreover, the wind density is so high that radiative cooling is significant.

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REFERENCES


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