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THE LOCATION OF THE Ca II IONS IN THE BETA PICTORIS DISK[1]

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ABSTRACT

Echelle spectra of β Pictoris have been obtained in the region of the Ca II λ8542 line which arises from the metastable $3d\ ^2D_{5/2}$ level. A narrow, weak, circumstellar absorption line is seen at the stellar radial velocity. A simple theory is developed of the radiative pumping of the metastable levels of the Ca II ions by the radiation from the star at the H and K lines. The relatively large fractional population, N_3(Ca II)/N_1(Ca II) ≈ 0.05, observed for the metastable level then requires that the calcium absorbers be largely concentrated within about 1 AU of the star. This result confirms two previous, independent estimates of the location of this gas. A time-variable circumstellar component of the λ8542 line also is found at an infall velocity of about 15 km s^{-1}.

Subject headings: line formation — stars: circumstellar shells

I. INTRODUCTION

Since the discovery with the *IRAS Observatory* of a number of main-sequence stars which show an infrared excess (Aumann *et al.* 1984), direct imaging has proved in the case of β Pictoris that this excess is caused by a disk of dust surrounding the star (Smith and Terrile 1984). The favorable orientation of the β Pic disk, which is viewed nearly edge-on from Earth, has permitted the further detection of its gaseous component, which may contain most of the circumstellar (CS) mass. The observed gas consists generally of low-ionization material somewhat similar to that in interstellar H I regions. Its temperature is $T_k \lesssim 4200$ K, and a typical density is n(H) $\approx 10^5$ cm^{-3} (Kondo and Bruhweiler 1985; Hobbs *et al.* 1985; Vidal-Madjar *et al.* 1986, hereafter Paper II).

Subsequent observations of β Pic have emphasized the complex time variations of the CS absorption lines of Ca II, Mg II, Fe II, and, unexpectedly, Al III. These lines appear to show an unvarying, relatively strong component centered at the stellar radial velocity. This stable component is sporadically augmented by variable, redshifted absorption features, with velocities up to 120 km s^{-1} in the case of Mg II (Lagrange, Ferlet, and Vidal-Madjar 1987; Ferlet, Hobbs, and Vidal-Madjar 1987). The stable component of these lines probably is produced at about 0.5 AU from the star by material released through evaporation of the orbiting dust particles by the intense starlight (Paper II). The variable features may arise from material which is nearer to the stellar surface and which is falling into the star. If the CS disk is a protoplanetary system, a plausible interpretation is that this variable absorption reveals the evaporation of solid, comet-like bodies (Lagrange-Henri, Vidal-Madjar, and Ferlet 1988, hereafter Paper VI).

It is important to obtain further, independent estimates of the distances from β Pic to both postulated kinds of absorbing gas, in order to test the validity of this somewhat speculative general picture. Owing to radiative pumping by β Pic, the populations of the metastable $3d$ levels of Ca II ions should depend sensitively on this distance, in the relevant range beyond about 1 AU. This *Letter* reports observations of the Ca II 8542 Å line, which arises from a metastable level, that do provide such independent information.

II. THE METHOD

a) Theory

The excitation energies of the five lowest lying levels of Ca II are given in Table 1. Because radiative decays of the $3d$ levels to the ground $4s$ level are parity-forbidden, the $3d$ levels are strongly metastable. Table 2 gives the transition probabilities A_{ij}, and the corresponding oscillator strengths f_{ij}, for the various lines connecting the levels listed in Table 1 (Wiese, Smith, and Miles 1969).

The relative populations n_2/n_1 and n_3/n_1 of Ca II ions must be estimated in the CS disk around β Pic, where $n_i(i = 1, 2, \ldots, 5)$ refers to the levels in Table 1 in order of increasing excitation. Three simplifying approximations will be adopted.

1. The five-level model atom of Table 1 is used.
2. All collisional transition rates in the disk should affect the $3d$ populations negligibly and therefore are ignored.
3. Radiative transfer effects (i.e., internal absorption) within the disk will be treated schematically, as is evident below.

Under the first two assumptions, the equations of statistical equilibrium which describe the steady state populations of the Ca II levels at any point in the disk are

$$A_{21}X_2 + A_{31}X_3 + A_{41}X_4 + A_{51}X_5 = R_{14} + R_{15}\ , \quad \text{(1a)}$$

$$-(R_{24} + R_{25} + A_{21})X_2 + A_{42}X_4 + A_{52}X_5 = 0\ , \quad \text{(1b)}$$

$$-(R_{35} + A_{31})X_3 + A_{53}X_5 = 0\ , \quad \text{(1c)}$$

and

$$-R_{24}X_2 + (A_{41} + A_{42})X_4 = R_{14}\ , \quad \text{(1d)}$$

where $X_i = n_i/n_1(i = 2, 3, 4, 5)$, the A_{ij} (s^{-1}) are the usual Einstein coefficients, and the $R_{ij} = B_{ij}J_{ij}$ are total line absorption rates (s^{-1}) in a local radiation field of average intensity J_{ij} (ergs s^{-1} cm^{-2} sr^{-1}). The quantities $B_{ij} = (g_j/g_i) \times (c^2/2h\nu^3) \times A_{ji}$ are the Einstein coefficients for absorption. The populations $X_i(d)$ depend on the distance d from the star through the intensities $J_{ij}(d)$.

Sufficiently near the star, the forbidden-line decays ($3d$–$4s$) are negligible in comparison with infrared-triplet absorptions ($3d$–$4p$), in depopulating the metastable levels. In this asymptotic region, defined by setting $A_{21} = A_{31} = 0$ in the equations

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TABLE 1

Ca II ENERGY LEVELS

Term	J	$E/hc(\text{cm}^{-2})$	E(eV)
$3p^6 4s\ ^2S$	1/2	0.	0.
$3p^6 3d\ ^2D$	3/2	13650.2	1.69
	5/2	13710.9	1.70
$3p^6 4p\ ^2P$	1/2	25191.5	3.12
	3/2	25414.4	3.15

above, analytic solutions of the equations can be obtained straightforwardly, and they show that these limiting values of both X_2 and X_3 are independent of d. Outside the asymptotic zone, in contrast, the forbidden-line decays dominate. Because the rates of spontaneous emission are independent of distance, while all of the absorption rates vary as $J_{ij}(d) \propto d^{-2}$, the $3d$ populations also decrease approximately as d^{-2}, at large distances.

b) *Application to β Pictoris*

If absorption of the star's light within the disk is otherwise ignored, the local absorption rates for Ca II ions at $d \gg R$ in a CS disk are given in equations (1) by

$$B_{ij} J_{ij}(d) = (R/d)^2 F_\nu B_{ij}/4\pi \ , \qquad (2)$$

where R is the stellar radius and F_ν is the emergent monochromatic flux at the stellar surface, which is assumed to vary negligibly with ν over the width of the (relatively narrow) CS absorption line.

Numerical solutions of equations (1) for the fractional populations $X_2(d)$ and $X_3(d)$ of the metastable levels have been obtained for the β Pic disk. The results shown by the upper pair of curves in Figure 1 were calculated using equation (2) with the values of R^2F_ν shown in Table 2. Because internal absorption of the light from β Pic has been otherwise ignored in the disk, these results should represent upper limits on the actual populations, at least outside the asymptotic zone. The most important results in Figure 1 are the large asymptotic populations $X_2 \approx X_3 \approx 0.1$ and the position of the outer boundary of that region near 1 AU. If our previous hypothesis that most of the Ca II absorption arises in a thin shell at $d \approx 0.5$ AU is correct (Paper II), then quite weak but detectable CS absorption should be observed at the centers of at least the λ8542 and the λ8662 infrared-triplet lines. In contrast, if most of the absorbers lie beyond 10 AU, the sharply reduced radiative pumping of the metastable levels by β Pic will be evident in negligible CS infrared-triplet absorption.

Radiative transfer effects within the disk can be qualitatively understood as follows. Our spectra indicate directly that the CS disk is optically thin in all lines of Ca II except H and K ($4s$–$4p$). An overestimate of the effects of internal absorption by the disk within these latter lines is obtained by reducing the H and K fluxes used in equation (2), and therefore assumed to be incident on the *inner* edge of the disk, by the factor corresponding to the actual CS absorption observed through the full disk in our various K-line profiles, i.e., observed in the flux actually emergent instead from the *outer* edge of the disk. The lower pair of curves in Figure 1 shows the results when the H and K fluxes listed in Table 2 are reduced by an additional factor of 0.078 to account schematically for the absorption by the full disk. The resulting population fractions $X_2(d)$ and $X_3(d)$ should give approximate lower limits to the actual values expected in the disk.

A variant of this general method has been similarly applied to Fe II ions in the β Pic disk by Kondo and Bruhweiler (1985).

III. OBSERVATIONS

Observations with the CAT telescope and the CES spectrograph were conducted at the European Southern Observatory during 1987 November. The detector used was either a Reticon which gave a resolving power $\lambda/\Delta\lambda \approx 10^5$ or a CCD which yielded $\lambda/\Delta\lambda \approx 6 \times 10^4$. A log of the observations is given in Table 3. The λ8498 and λ8542 lines of Ca II were both recorded in a single Reticon exposure, while only the stronger λ8542 line

TABLE 2

Ca II LINES

λ_{air}(Å)	Lower Level	Upper Level	$A_{ij}(\text{s}^{-1})$	f_{ij}	R^2F_ν[a]	F_0/F_c
3933.66.........	$4s\ ^2S_{1/2}$	$4p\ ^2P_{3/2}$	1.50×10^8	0.69	1.8	0.26
3968.47.........	$4s\ ^2S_{1/2}$	$4p\ ^2P_{1/2}$	1.46×10^8	0.344	1.8[b]	0.27[b]
7291.46.........	$4s\ ^2S_{1/2}$	$3d\ ^2D_{5/2}$	1.3	2.4×10^{-8}	4.7	1.0
7323.88.........	$4s\ ^2S_{1/2}$	$3d\ ^2D_{3/2}$	1.3	1.6×10^{-8}	4.7	1.0
8498.02.........	$3d\ ^2D_{3/2}$	$4p\ ^2P_{3/2}$	0.111×10^7	0.012	4.1	0.91
8542.09.........	$3d\ ^2D_{5/2}$	$4p\ ^2P_{3/2}$	0.99×10^7	0.072	3.5	0.77
8662.14.........	$3d\ ^2D_{3/2}$	$4p\ ^2P_{1/2}$	1.06×10^7	0.060	3.8	0.84

[a] The product R^2F_ν for β Pic in units of 10^{18} ergs s^{-1} Hz^{-1}, where R is the stellar radius and F_ν is the emergent surface flux at the center of the relatively broad photospheric absorption line. The adopted intensity at line center relative to that in the adjacent continuum is given in the last column, as determined from our spectra. The absolute monochromatic luminosity in the adjacent continuum was estimated by interpolation between the corresponding values for α CMa (A1 V) and α Aql (A7 V) determined from the relation $R^2F_\nu = r^2 f_\nu$, where f_ν is the flux at Earth and r is the stellar distance. The measured fluxes plotted by Code *et al.* 1976 were extrapolated to $\lambda > 7000$ Å via the model atmospheres of Kurucz 1979, which were also used as a guide to the interpolation among the three spectral types.

[b] No discernible (rotationally broadened) photospheric Ca II H line is present. However, the adjacent "continuum" flux has been reduced by an additional factor of 0.27, determined from our spectra, to account for the presence of the overlapping Balmer Hϵ line. The fractional population specifically of the $3d\ ^2D_{5/2}$ level is virtually independent of the average intensity at the Ca II H line, in the five-level approximation without collisions. As expected, the populations of both metastable levels are effectively independent of the average intensities at the forbidden $\lambda\lambda$7291, 7324 lines as well.

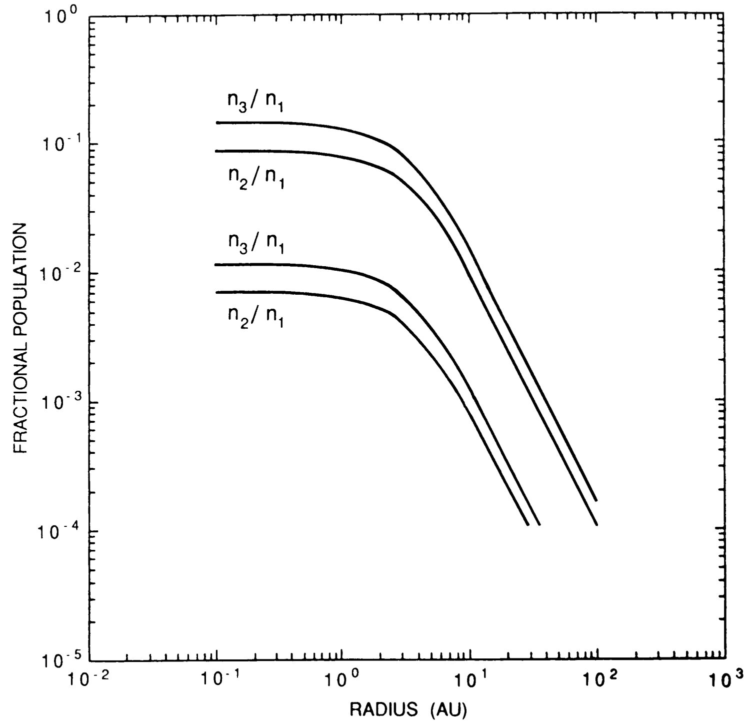

FIG. 1.—The theoretical fractional populations, $X_2 = n_2/n_1$ and $X_3 = n_3/n_1$, of the metastable 3d levels of Ca II ions, as a function of radial distance within the circumstellar disk of β Pic. The two upper curves give the approximate upper limits obtained when, at any point, the interior disk is incorrectly assumed to be entirely transparent to the star's light, even near the H and K lines. The two lower curves give the approximate lower limits on X_2 and X_3 which are obtained by a method discussed in the text.

was recorded with the CCD. The procedure for the reduction and analysis of the Reticon spectra, detailed by Ferlet and Dennefeld (1984), was carried out with the standard IHAP software at the Institut d'Astrophysique de Paris. The precision of the radial velocities deduced from the absolute scale of wavelengths is ± 0.5 km s^{-1}.

The λ8542 line in the CCD spectrum of β Pic acquired on November 21 is shown in Figure 2. The reduction of the CCD exposures is complicated by the presence of appreciable interference fringes in the infrared region. The spectrum of β Pic therefore was divided by that of a standard star, HR 2294, in order to obtain the result in Figure 2. The division in fact removed simultaneously both the interference fringes and the numerous, well-known telluric lines of water vapor in this wavelength region. The broad, strong photospheric λ8542 line is seen to be slightly asymmetric, owing to blending with the Paschen line $P15$ at 8545.5 Å.

The principal result is that a weak CS absorption line is unambiguously detected at the stellar radial velocity of 21 ± 3 km s^{-1} determined from our spectrum. The equivalent width and the heliocentric velocity of the CS line are $W_\lambda(8542) = 4 \pm 1$ mÅ and $V_h = 21 \pm 1$ km s^{-1}, respectively. It should be noted that faulty CCD pixels distorted the raw data near $V_h \approx 40$ km s^{-1}, and that the corresponding part of the profile is therefore untrustworthy.

Reticon spectra were obtained at the K line and at the λ8542 line, respectively, within an interval of only about 1 hr on November 17 (Table 3). The Reticon data show more noise than those from the CCD, and no standard star spectrum was obtained at the triplet lines to allow removal of the telluric features. Nevertheless, the CS λ8542 component, as well as its much stronger K-line counterpart, are clearly present at $V_h = 21 \pm 1$ km s^{-1}. The equivalent widths are $W_\lambda(8542) = 5 \pm 2$ mÅ and $W_\lambda(\mathrm{K}) = 82 \pm 5$ mÅ. A long-wavelength wing on the CS K line extends nearly to $V_h \approx 40$ km s^{-1}; the noise in the λ8542 profile precludes a possible similar detection. We recall that bad CCD pixels obscured some of the same region in Figure 1.

Finally, the Reticon λ8542 spectrum of November 28 shows two resolved CS components. The presumably stable, central

TABLE 3

OBSERVATIONAL DATA

Date (1987)	Detector	Line	Component 1 W_λ(mÅ)	Component 1 V_h(km s^{-1})	Component 2 W_λ(mÅ)	Component 2 V_h(km s^{-1})
Nov 17.........	Reticon	8542	5 ± 2	22 ± 1	...	...
		K	82	21 ± 1	Red wing to +40 km s^{-1}	
Nov 21.........	CCD	8542	4 ± 1	21 ± 1	...	...
Nov 25.........	Reticon	K	83	22 ± 1	30	33 ± 1
Nov 28.........	Reticon	8542	2 ± 1	21 ± 1	7 ± 3	36 ± 2
Nov 29.........	Reticon	K	80	20 ± 1	37	35 ± 1

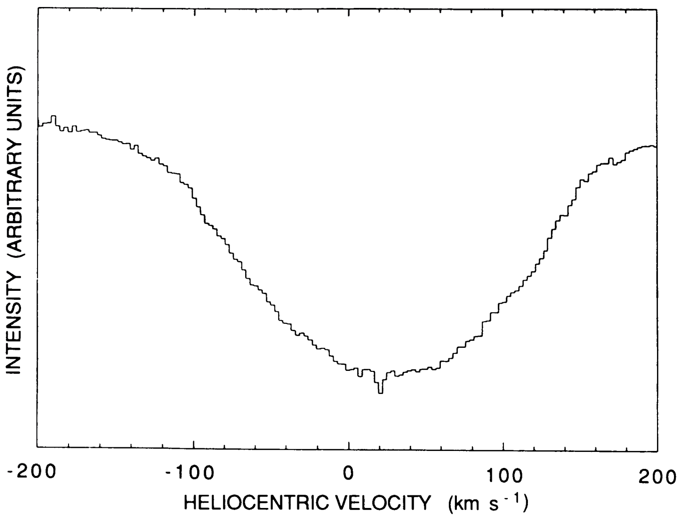

FIG. 2.—A CCD spectrum of β Pic at the Ca II λ8542 line on November 21, after division by the spectrum of the standard star HR 2294 in order to remove the telluric lines and the CCD interference fringes. The central residual intensity of the broad stellar line is about 0.77 (Table 2); the true zero-point of intensity falls well below the bottom of the panel.

component seen previously is marginally detected again, but a stronger component with $W_\lambda(8542) = 7 \pm 3$ mÅ is observed at $V_h \approx 36$ km s^{-1}. Time-varying, redshifted absorption therefore also appears to arise from the metastable 3*d* levels of Ca II as well. The K line profiles obtained 3 days earlier (November 25) and 1 day later (November 29) each show a resolved, unambiguously detected component at a similarly redshifted velocity.

The observational data are summarized in Table 3; a fuller account will be given in a subsequent paper. The CS λ8498 line, which is expected to be weaker by a factor of about 9 than its λ8542 counterpart, was not detected in either of the Reticon spectra.

IV. RESULTS

a) The Line Component at the Stellar Velocity

The central, apparently stable component at $V_h = 21$ km s^{-1} which is seen at the K line—and at those of Fe II and Mg II—is clearly present at the λ8542 line as well, with a strength $W_\lambda \approx 4$ mÅ. In the applicable optically thin limit, the corresponding column density of metastable Ca II ions is N_3(Ca II) $= 8.6 \times 10^{10}$ cm^{-2} (Spitzer 1978). Profile fitting of the same component of the K line, which shows $W_\lambda \approx 80$ mÅ, gives N_1(Ca II) $\approx 1.8 \times 10^{12}$ cm^{-2} (Paper II). Hence, along the light path through the entire CS disk, an average excitation fraction N_3(Ca II)/N_1(Ca II) ≈ 0.05 is found.

This observed, average fractional population $\langle X_3 \rangle = N_3/N_1 \approx 0.05$ of the $3d\,^2D_{5/2}$ metastable level substantially exceeds the theoretical lower limit shown by the lower curve in Figure 1 at all distances, including those within the asymptotic zone. On the other hand, an overestimate $d \lesssim 4$ AU is obtained from the upper curve, if Ca II is largely concentrated in a thin shell and if all absorption of the stellar H and K fluxes from β Pic in the interior parts of the disk is ignored. We conclude that most of this Ca II absorption occurs at a distance of order 1 AU. This is the principal result of these observations; it seems satisfactorily consistent with our previous inference that the Ca II ions are concentrated at $d \approx 0.5$ AU and therefore with the grain-evaporation hypothesis on which this view is based (Paper II). For example, the much reduced radiative pumping of the $^2D_{5/2}$ level which occurs at only $d = 20$ AU would yield $3 \times 10^{-4} \lesssim X_3 \lesssim 4 \times 10^{-3}$ (Fig. 1), which corresponds to $W_\lambda(8542) \lesssim 0.3$ mÅ. Such a hypothetical CS line would be much too weak to have been detected in our spectra.

b) Variable, Redshifted Line Components

Time-varying, redshifted absorption has been detected at the λ8542 line of Ca II, at approximately the same velocity as a variable component of the K line measured a few days earlier and later. This finding implies that such transitory material is also produced within a few AU of the star. Accurate measurements of the excitation fraction N_3(Ca II)/N_1(Ca II) have not yet been obtained in well-resolved line components at such velocities of infall, which amount to about 15 km s^{-1}. However, the spectra from November 25, 28, and 29 suggest that these excitation fractions may sometimes exceed the value 0.05 found for the stable line component at $+21$ km s^{-1}, and hence that this transitory material is produced even nearer to the star than is the stable component. The evaporation of comet-like bodies falling into the star is a plausible but not unique, interpretation of these variable spectral features.

This conclusion agrees with the result of Bruhweiler and Kondo (1985) derived from an analogous study of variable absorption from metastable Fe II levels. Those authors inferred that the Fe II ions are located at $d \lesssim 1$ AU.

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