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CIRCUMSTELLAR GAS ASSOCIATED WITH HL TAURI: EVIDENCE FOR A REMNANT INFALLING ENVELOPE

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ABSTRACT

We have discovered molecular carbon absorption lines in the spectrum of HL Tau near 8775 Å. These C_2 lines have a heliocentric radial velocity of 43 ± 3 km s^{-1}, redshifted by 23 ± 3 km s^{-1} relative to the star and the associated molecular cloud. This velocity difference suggests that the molecular carbon absorption arises in an infalling envelope. Since KI and diffuse interstellar bands are much weaker than expected, the chemical composition and/or excitation conditions in the HL Tau envelope appear to differ substantially from those in the interstellar medium.

Subject headings: stars: circumstellar shells — stars: pre–main-sequence

I. INTRODUCTION

Studies carried out over the past 5 yr provide strong evidence for circumstellar disks associated with many pre–main-sequence stars (see Strom, Edwards, and Strom 1988 for a recent review). The most persuasive evidence comes from observations of the T Tauri star HL Tau. Its broad infrared energy distribution must arise from dust at a wide range of temperatures and distances from the central pre–main-sequence star. The optical depth of the dust at 100 μm is ~1, which implies a visual optical depth of ~1000 (Adams, Lada, and Shu 1987; Edwards *et al.* 1987). In order to account for the fact that HL Tau is visible at optical wavelengths, it is necessary to assume that its infrared excess arises in an optically thick but physically thin circumstellar envelope: e.g., a disk.

Further indirect evidence of a disk comes from high spectral resolution observations of [O I] and [S II] emission lines. These forbidden lines appear to be associated with the outer ($r \sim 100$ AU) regions of a wind driven by HL Tau. However, only blueshifted emission is observed, suggesting the presence of a structure whose opacity and dimension is sufficient to obscure the receding part of the outflowing gas (Appenzeller, Jankovics, and Östreicher 1984; Edwards *et al.* 1987).

Direct and speckle images at near-infrared wavelengths (Grasdalen *et al.* 1984; Beckwith *et al.* 1984) reveal a flattened, disklike structure associated with HL Tau. Millimeter line and continuum observations of HL Tau made with the Owens Valley Radio Observatory provide compelling evidence for an inclined disk of diameter ~4000 AU. The radial velocity data indicate that the material in the disk (total mass ~0.01–0.1 $M_\odot$) is in Keplerian orbit about the central star (Sargent and Beckwith 1987).

Cohen (1983) was the first to suggest that HL Tau might be viewed through an *edge-on* disk. He pointed out that it had an unusually large ratio of infrared to visual luminosity, ~630, which implies a visual extinction $A_v \sim 7$ mag. It is also unique among T Tauri stars in showing a strong 3.05 μm ice band absorption feature, as well as a strong silicate absorption feature near 9.5 μm.

Beckwith *et al.* (1986) suggested that the massive disk surrounding HL Tau is a structure from which planets will eventually evolve. Since the only high-resolution observations made were in light scattered by dust, it is important to assess the gas content of the system. We report in this *Letter* the results of a spectroscopic study aimed at both learning whether gas is associated with dust in the HL Tau circumstellar environment and probing the kinematics and chemistry of the gas.

II. OBSERVATIONS AND REDUCTIONS

We chose C_2 as our probe of the gas along the line of sight to HL Tau. The 2–0 band of the Phillips system of C_2 falls in the 8775 Å region, where HL Tau is sufficiently bright to allow high-resolution spectroscopic study. This band has been observed in several highly reddened stars (e.g., Lutz and Crutcher 1983; Hobbs, Black, and van Dishoeck 1983; Gredel and Münch 1986). Using the relationship between $N(C_2)$ and $E(B-V)$ given by Gradel and Münch (1986) and an $E(B-V)$ of 2.3 ($A_v \sim 7$), we expect that the strongest feature in this C_2 band will have an equivalent width of 50 mÅ if 30 K $\lesssim T \lesssim$ 300 K.

In 1984 October we used the Echelle/CCD combination at the Mayall telescope at KPNO to obtain high spectral resolution observations of the 8775 Å region for HL Tau, along with the heavily reddened B supergiant Cyg OB2 12 [$E(B-V) = 3.35$; Schulte 1958]. We also observed HL Tau in

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1986 October at lower resolution, but with greater wavelength coverage with the new UV-fast camera.

We corrected for pixel-to-pixel variations in sensitivity by dividing our spectra by exposures of a quartz lamp. We extracted the order containing the C_2 and geometrically transformed the subarray to correct for the tilt of the dispersion axis with respect to the projected slit. We derived the relation between wavelength and pixel position from a daylight spectrum. Our effective resolution is 0.25 Å, based on Gaussian fits to unresolved spectral lines.

Proper subtraction of telluric emission lines and scattered skylight is critical for HL Tau; for a 1 hr exposure at $\lambda \sim 8775$ Å, night sky emission is strong even at the resolution $R \sim 35{,}000$. We obtained the telluric emission spectrum from the array by summing all rows on the chip not exposed to HL Tau or nearby XZ Tau. Figure 1 contains the spectra of (*a*) HL Tau derived from 473 minutes of integration, (*b*) HL Tau after sky subtraction along with the predicted positions of the C_2 band (S/N = 94), (*c*) the M3 III standard star HR 3576, and (*d*) Cyg OB2 12.

The spectrum of HL Tau in Figure 1*b* has clear evidence of C_2. We verified its presence by examining our later spectra taken in 1986 October. By summing the strongest C_2 lines in HL Tau using a shift-and-add procedure and comparing the resulting composite feature with a similar composite from HR 3576, we conclude that the photospheric contribution to the C_2 spectrum is minimal.

Table 1 summarizes the data for all C_2 lines identified in the spectra of HL Tau and Cyg OB2 12. For both stars it was necessary to deblend the $R(4)R(8)$, $R(2)R(10)$, $R(0)R(12)$, and $P(4)Q(8)$ pairs. Some of the C_2 lines in HL Tau were also deblended from photospheric lines. By averaging the radial velocities of all observed C_2 lines, we find the heliocentric radial velocity toward Cyg OB2 12 to be -2.1 ± 0.4 km s^{-1}; toward HL Tau, 43 ± 3 km s^{-1}.

Using 11 photospheric lines in HL Tau (all of which are quite strong in HR 3576), we find that HL Tau itself has a heliocentric radial velocity of 20 ± 2 km s^{-1}. Calvet, Cantó, and Rodríguez (1983) found the velocity of the surrounding molecular cloud to be 18.1 km s^{-1}. Thus the C_2 lines in the direction of HL Tau are redshifted with respect to the photospheric lines and the molecular cloud by 23 ± 3 km s^{-1}.

We used the column densities derived from the measured equivalent widths to construct standard temperature plots for Cyg OB2 12 and HL Tau (Fig. 2). The errors stated in Table 1 are statistical only. We have not estimated the additional systematic errors due to telluric or photospheric contamination. Our results for Cyg OB2 12 are very similar to those of Lutz and Crutcher (1983), requiring a two-temperature fit to match the data: $T = 61 \pm 2$ K for the lower rotational states and $T = 250 \pm 50$ K for the higher. For HL Tau, we find a temperature of 105 ± 12 K characterizes the distribution over all J-values. We used these temperatures to construct partition functions and find the total $N(C_2)$ for HL Tau and Cyg OB2 12 to be $4.2 \pm 0.9 \times 10^{14}$ cm^{-2} and $4.2 \pm 0.5 \times 10^{14}$ cm^{-2}, respectively.

The similarity between total C_2 column densities for Cyg OB2 12 and HL Tau leads one to expect that the spectra would also contain similar KI absorption features. Chaffee and White (1982) found the equivalent widths at $\lambda 7664$ and $\lambda 7698$ in Cyg OB2 12 to be 430 and 323 mÅ respectively. We have searched the HL Tau spectra obtained in 1986 October for evidence of KI absorption and find the upper limits of the two lines to be only 54 and 33 mÅ, respectively.

We have also searched our spectra of HL Tau for evidence of diffuse interstellar bands (DIBs; Sanner, Snell, and Vanden Bout 1978; Sneden *et al.* 1978), using additional lower resolution (1.8 Å) spectra (obtained with the Gold Cam Spectrograph at KPNO in 1987 November) to study the 6000 Å

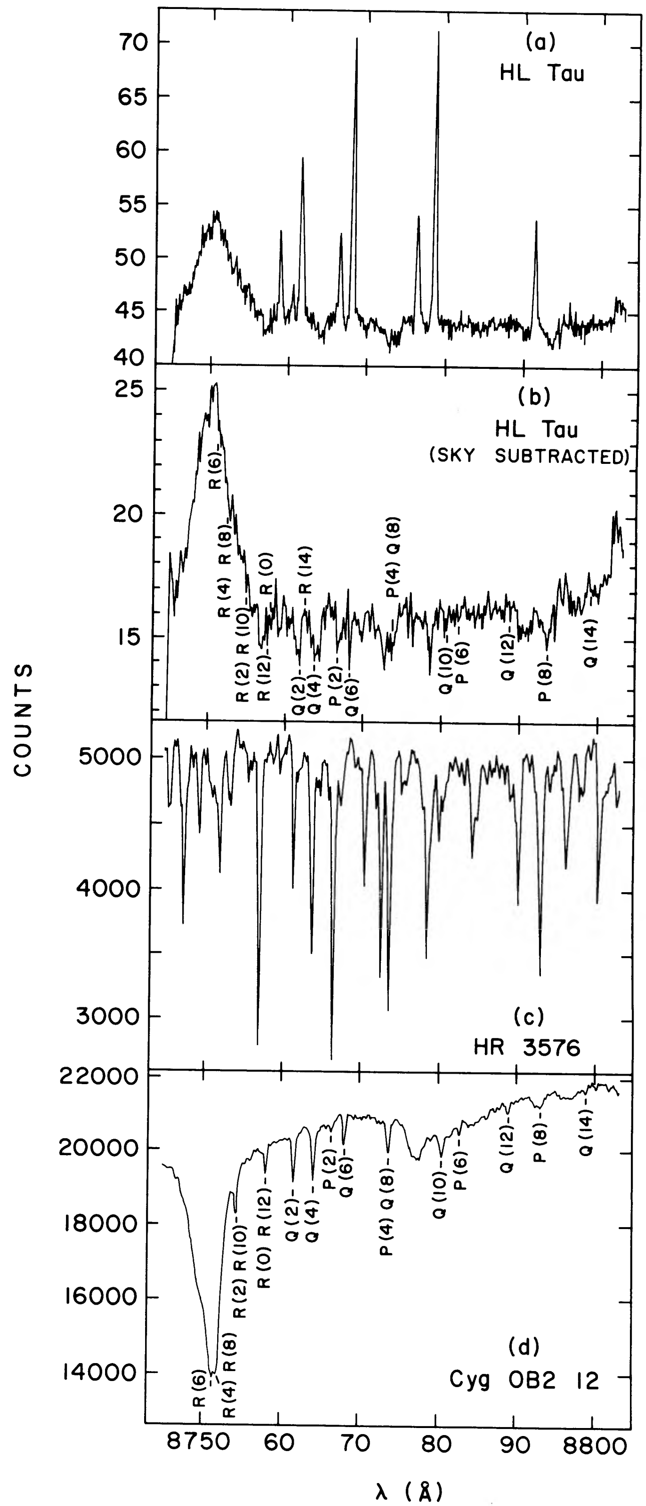

FIG. 1.—Plots of intensity vs. wavelength derived from our Echelle spectra for (*a*) HL Tau prior to subtraction of telluric emission; (*b*) HL Tau after sky subtraction; (*c*) HR 3576, an M3 III standard; and (*d*) Cyg OB2 12.

TABLE 1

SPECTRAL DATA FOR HL TAURI AND CYGNUS OB2 12

		HL TAU			CYG OB2 12		
LINE	λ_{lab} (Å)	$v_{\odot}$ (km s^{-1})	W_{λ}[a] (mÅ)	N_J (10^{13} cm^{-2})	$v_{\odot}$ (km s^{-1})	W_{λ}[b] (mÅ)	N_J (10^{13} cm^{-2})
R (0)..........	8757.57	41	9.8	1.6 ± 0.6	−2.1	16	2.6 ± 0.2
P (2)..........	8765.91	48	25[c]	42.6 ± 5.9	−1.7	4.8	8.0 ± 1.6
Q (2)..........	8761.08	46	45[c]	15.2 ± 1.2	−1.7	25	8.2 ± 0.3
R (2)..........	8753.83	56	14	5.9 ± 1.5	−2.1	16	6.8 ± 0.4
P (4)..........	8773.31	41	2.2	2.2 ± 3.5	−3.5	14	13.7 ± 1.0
Q (4)..........	8763.62	30	51[c]	17.0 ± 1.2	−2.4	36	11.9 ± 0.3
R (4)..........	8751.54	60	13	6.6 ± 1.8	−4.8	6.1	3.1 ± 0.5
P (6)..........	8782.17	21	14	12.1 ± 3.1	−1.1	4.6	4.0 ± 0.8
Q (6)..........	8767.62	43	50	16.7 ± 1.2	−2.1	14	4.5 ± 0.3
R (6)..........	8750.71	42	5.2	2.8 ± 1.9	−2.8	8.1	4.4 ± 0.5
P (8)..........	8792.52	52	7.8[c]	6.3 ± 2.8	−0.8	0.8	0.6 ± 0.8
Q (8)..........	8773.09	41	12	4.1 ± 1.2	−3.5	8.3	2.8 ± 0.3
R (8)..........	8751.33	60	9.7	5.5 ± 2.0	−4.8	3.3	1.9 ± 0.5
Q (10)..........	8780.02	42	10[c]	3.4 ± 1.2	−4.2	13	4.4 ± 0.3
R (10)..........	8753.41	...	...	...	−2.1	2.2	1.3 ± 0.6
Q (12)..........	8788.42	42	1.2	0.4 ± 1.2	−1.4	4.7	1.6 ± 0.3
R (12)..........	8756.94	47	13	8.0 ± 2.1	−2.1	2.5	1.5 ± 0.6
Q (14)..........	8798.30	38	1.0	0.3 ± 1.2	0.6	2.4	0.8 ± 0.3
R (14)..........	8761.94	43	1.1	0.7 ± 2.1	...	...	...

[a] σ_w is 3.5 mÅ for all HL Tau lines, based on the mean S/N for the spectrum. For those lines for which $W_{\lambda} < \sigma_w$, the stated W_{λ} represents an upper limit.

[b] σ_w is 1.0 mÅ for all Cyg OB2 lines, based on the mean S/N for the spectrum.

[c] This line was deblended from a photospheric line.

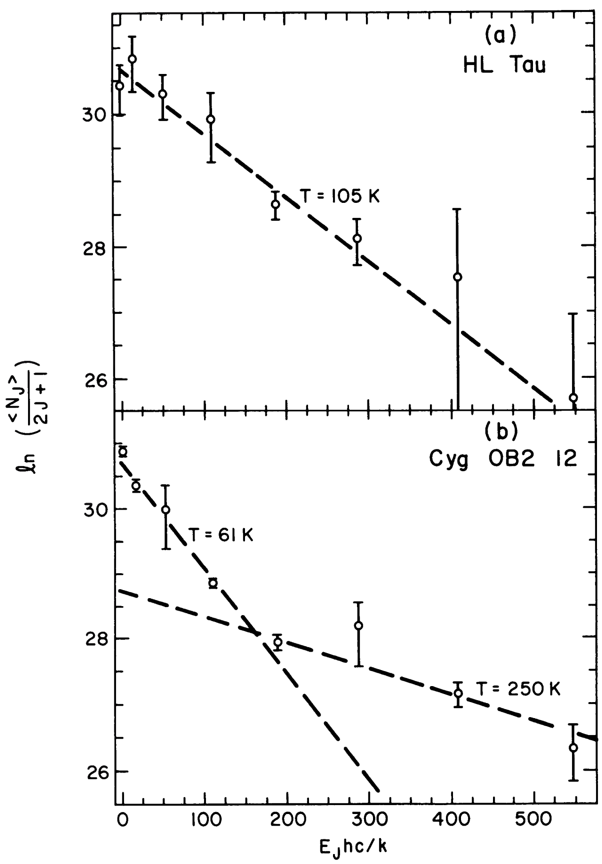

FIG. 2.—Standard temperature plots for (a) HL Tau and (b) Cyg OB2 12. The vertical axis is ln [$\langle N_J \rangle/(2J + 1)$], and the horizontal axis is $E_J hc/k$. The temperature is thus the negative inverse of the slope.

region. The strongest lines expected should have equivalent widths of 1250 mÅ at 6283 Å, 600 mÅ at 6613 Å, and 760 mÅ at 8612 Å, but the observed equivalent widths are only 127 mÅ, 184 mÅ, and 100 mÅ, respectively.

III. DISCUSSION

The observation that the C_2 features are *redshifted* relative to the star leads us to conclude that C_2 traces gas which is *infalling* toward HL Tau. *This gas cannot be located in a disk orbiting HL Tau.* If we assume that the gas is in free-fall and surrounds a star of 1 $M_{\odot}$, the region traced by the observed lines must be located at a distance $r \sim 3.3$ AU from the stellar surface. If the grains are perfect radiators, then the expected grain temperature at this radius is 252 K for an assumed total luminosity of 7.2 $L_{\odot}$ (Cohen 1983), while our results give $T = 105$ K. Several effects might account for this apparent discrepancy: e.g., extinction in the infalling material, the possible lack of coupling between the grain and gas temperatures, and the actual optical properties of the grains.

The conclusion that HL Tau is surrounded by an infalling envelope traced by C_2 suggests that the ice and silicate features need not arise from dust embedded within a disk viewed edge-on, but might more naturally arise from dust located in the envelope. Shu, Adams, and Lizano (1987) reached this conclusion on the basis of photometric evidence. The unusually flat infrared spectrum of HL Tau finds natural explanation if the excess emission at $\lambda \gtrsim 10$ μm arises primarily from reprocessing of optical radiation emanating from HL Tau by dust in the envelope (Adams, Lada, and Shu 1988).

The weakness of the DIBs and KI absorption features suggests that the chemistry of the dust and gas in the HL Tau envelope differs significantly from that in the interstellar medium. It is possible, for example, that potassium has been depleted onto grain surfaces in the higher density, protostellar core environment.

In order to use the C_2 column density to determine a mass infall rate, we must determine the behavior of the density of the circumstellar material with distance from HL Tau. If we start with the relation $\Phi(r) = 4\pi r^2 n(r) v(r)$, where Φ is the particle flux through a particular annular shell and $n(r)$ is the number density at that radius, and we assume a free-fall velocity field $v^2 = 2GM_*/r$, we obtain the result for the number density as a function of velocity $n(v) = \Phi/(4\pi GM_*)$. This result is valid for $0 \leq v \leq v_d$, where v_d is the velocity at the C_2 destruction front. Thus each absorption feature would be a square well. Our line centers would correspond to half that Doppler shift. Since our lines are shifted by 23 km s^{-1} with respect to HL Tau, this would produce spectral lines broadened to a full width at half-maximum (FWHM) of roughly 1.3 Å, which is much broader than our average FWHM of 0.28 Å. The most plausible explanation of this discrepancy is that the C_2 does not exist in the outer, lower velocity regions of the infalling circumstellar material. Instead, it may be created from parent molecules at some creation front in the circumstellar nebula. If we again take 23 km s^{-1} to be intermediate between the velocity at the C_2 creation and destruction fronts and assume a mass for HL Tau of 1 $M_\odot$, these fronts will be 5.3 and 2.3 AU from HL Tau, respectively.

Setting $N(C_2)$ equal to the number density integrated between the C_2 creation and destruction fronts gives $N(C_2) = \Phi(v_d - v_c)/(4\pi GM_*)$, where v_d and v_c are the velocities at the destruction and creation fronts, and Φ refers only to the flux of C_2. Substituting for the parameters in the equation gives $\Phi = 8.06 \times 10^{35}$ C_2 molecules per second. If the ratio of hydrogen to C_2 is 6.6×10^7:1 (as derived from our observations of Cyg OB2 12), then the mass accretion rate, $\dot{M}$, onto HL Tau is 1.3×10^{-6} $M_\odot$ yr^{-1}.

We can now apply this value to the relation $L_a R_* = GM_* \dot{M}$ (L_a is the total accretion luminosity; Shu, Adams, and Lizano 1987). If we assume that the accretion luminosity dominates the photospheric luminosity of HL Tau, the radius required by this relation is roughly 6 $R_\odot$. We conclude that the mass infall we have discovered produces a significant, if not dominant, component of the total luminosity of the HL Tau system.

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