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INFRARED CO EMISSION FROM YOUNG STARS: HIGH-RESOLUTION SPECTROSCOPY

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ABSTRACT

We have detected the high-density, high-temperature, neutral material within 10–200 $R_{\odot}$ of five young stars through high-resolution (20–40 km s^{-1}) spectroscopy of the first overtone bands of CO at 2.3 μm. We find a remarkable diversity in the band head profiles toward these sources, ranging from distinctly double-peaked (DG Tau), through broad bumps with emission extending up to 200 km s^{-1} from the stellar velocity (WL 16, NGC 2024 IRS 2, and S106 IRS 4), to narrow lines having a FWHM velocity of $\sim$50 km s^{-1} (SVS 13). Both the profiles and the fluxes of WL 16, NGC 2024 and S106 can be fitted by emission from Keplerian accretion disks. DG Tau is well described by the superposition of emission from a Keplerian accretion disk and the diluted photospheric absorption features of an M0 dwarf. SVS 13 requires either a disk rotating at velocities slower than Keplerian, or a nearly face-on Keplerian disk plus an additional, broad velocity component, possibly the acceleration region of a neutral disk wind.

Subject headings: accretion, accretion disks — circumstellar matter — infrared: stars — line: profiles — stars: formation — stars: pre–main-sequence

1. INTRODUCTION

It is now well established that young stars go through a phase of accretion accompanied by mass loss before reaching the main sequence. Accretion disks are inferred to exist from broad-band continuum measurements at all wavelengths from the UV (where the emission is thought to be accretion luminosity from the boundary layer between the disk and the star: Kenyon & Hartmann 1987; Bertout, Basri, & Bouvier 1988) to the millimeter (where the emission originates from dust in the disk on scales $\sim$100 AU: Beckwith et al. 1990).

Scoville et al. (1983) discovered through high-resolution FTS spectroscopy of the Becklin-Neugebauer object that the first overtone rotation-vibration bands of CO trace neutral material at high temperatures (few 1000 K) and densities ($n \gtrsim 10^{10}$ cm^{-3}) within a few stellar radii near young stars (see also Geballe & Persson 1987; Carr 1989). With the new cooled echelle spectrometers on the infrared telescopes in Hawaii, it is now possible to extend high-resolution spectroscopy to lower luminosity objects (e.g., Carr & Tokunaga 1992; Carr et al. 1993). Here we present new observations of three low-mass objects, SVS 13, DG Tau and WL 16, and two high-mass stars, S106 IRS 4 and NGC 2024 IRS 2. We show that the spectra can be successfully explained as originating in disks within 10–200 $R_{\odot}$ of the central object. Models of the band head emission from accretion disks and neutral winds are presented in a second paper (Chandler, Carlstrom, & Scoville 1993, hereafter Paper II).

2. OBSERVATIONS

The data were obtained using the facility instrument CGS 4, at the United Kingdom Infrared Telescope (UKIRT) on Mauna Kea, Hawaii. The positions, luminosities, and adopted extinctions and distances to the sources are listed in Table 1. All the observations were made in 1992 September apart from the spectrum of WL 16, which was obtained in 1991 June. Images were obtained using a cooled 62 × 58 InSb array. Low-resolution spectra, 440 km s^{-1}, were obtained using a 75 lines mm^{-1} grating; high-resolution spectra, 19 km s^{-1} (38 km s^{-1} for WL 16), were obtained using an echelle. The spectra were fully sampled by translating the array by $\frac{1}{2}$ pixel ($\frac{1}{3}$ pixel for WL 16), giving two detector positions (three for WL 16) per resolution element.

For the data taken in 1992 September, the sky frames were obtained at a position 10″ south of the program stars, aligned along the slit so that we obtained both positive and negative images. They were later combined to increase the signal-to-noise ratio. For WL 16, sky frames were obtained by switching 1′ away, off the array. Wavelength calibration was performed using an argon lamp, with additional observations of photospheric CO absorption features of late-type standard stars for the echelle data. The flux calibration was derived from observations of standard stars with a spectral type earlier than F6 v, which have no intrinsic CO features.

The data were reduced using the CGS 4 reduction software and IRAF. A continuum slope has been subtracted from the low-resolution spectra by interpolating published photometry at longer wavelengths (Cohen & Schwartz 1976; Aspin et al. 1990; Eislöffel et al. 1991) to the K band. For the high-resolution spectra, it is assumed that the continuum is flat over the small wavelength range covered by the echelle, so a constant offset has been fitted to the continuum to the short wavelength side of the band head and subtracted from the spectra. The low-resolution spectra are displayed in Figure 1, and the high-resolution spectra of the v = 2–0 band head are shown in Figure 2.

3. RESULTS AND DISCUSSION

3.1. *Low-Resolution Spectra*

The first four band heads in the low-resolution spectra have been fitted by an isothermal, LTE model, to obtain an estimate

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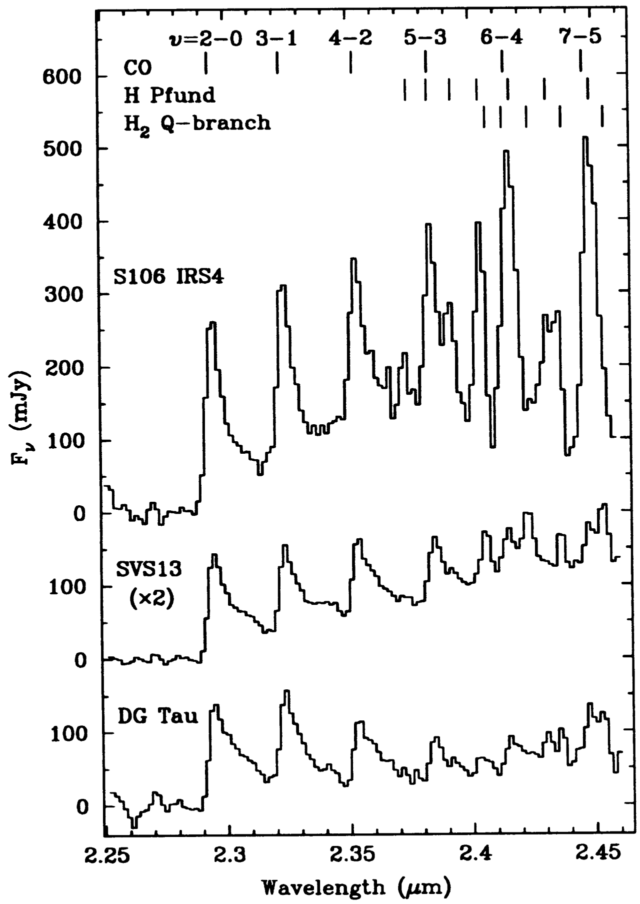

FIG. 1.—Low-resolution spectra of DG Tau, SVS 13, and S106 IRS 4. The wavelengths of the CO band heads, H Pfund series, and H_2 Q-branch lines are marked.

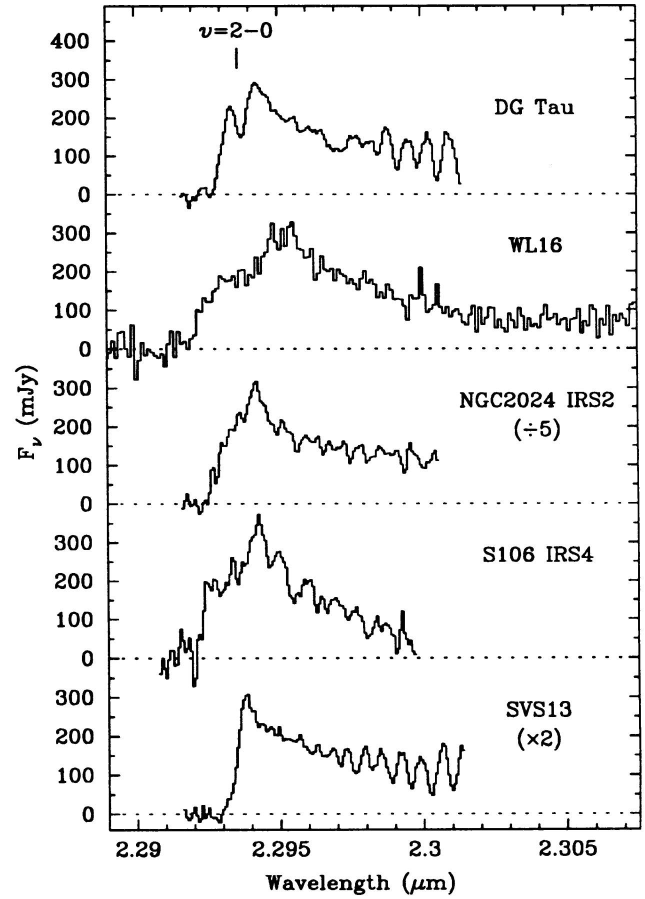

FIG. 2.—High-resolution spectra of the $v = 2$–0 band head. The wavelength of the $v = 2$–0 band head is marked. The resolution is 19 km s^{-1} for all sources apart from WL 16, which is 38 km s^{-1}. The rms measured to the blue of the band head is 6, 40, 74, 31, and 14 mJy, for SVS 13, S106, NGC 2024, WL 16 and DG Tau, respectively.

of the excitation temperature and optical depth of the CO emission. A Gaussian velocity profile with a FWHM of 50 km s^{-1} was assumed for fitting the low-resolution data of SVS 13 (see § 3.2.3), while 200 km s^{-1} was used for S106 (§ 3.2.1). For DG Tau the emission was found to be optically thin, and therefore the width of the assumed velocity distribution has a negligible effect on the derived temperature. The results, summarized in Table 1, are in good agreement with those found by Carr (1989). The fits to both SVS 13 and S106 indicate high optical depth in the overtone lines [$N(\mathrm{H}) \sim 10^{25}$ cm^{-2}].

The luminosity emitted in the observed CO overtone bands is given in Table 1, along with the minimum projected radius of the emission region, assuming $\tau_{2-0} \gg 1$ and spherical symmetry. We have no low-resolution data for WL 16 or NGC 2024, so we have used excitation temperatures of 4000 K

TABLE 1

OBSERVED YOUNG STELLAR OBJECTS AND DERIVED PARAMETERS FOR CO OVERTONE BAND HEADS

Source	α(1950)	δ(1950)	L_{bol} ($L_\odot$)	A_V (mag)	D (pc)	References	F_ν[a] (Jy)	T_{ex}[b] (K)	τ_{2-0}[c]	L_{CO}[d] ($L_\odot$)	R_{min}[e] ($R_\odot$)
SVS 13	03h25m58.2s	+31°05′46″	66	10	350	1, 2, 3	0.3	3600	2.3	2.6×10^{-2}	6.5
DG Tau	04 24 00.9	+25 59 36	9.4	2.4	140	4, 5, 6	1.2	2850	≪1	3.1×10^{-2}	3.2
WL 16	16 24 00.3	−24 30 44	22	31	160	7, 8, 9	0.5	...	...	...	8.0
NGC 2024	05 39 14.3	−01 55 59	$\sim 10^4$	20.5	415	10, 11, 12	7.8	...	...	...	34
S106 IRS 4	20 25 33.8	+37 12 50	2×10^4	13.5	600	13, 14	3.1	4800	1.1	4.0×10^{-1}	15

REFERENCES.—(1) Cohen, Harvey, & Schwartz 1985; (2) Liseau, Lorenzetti, & Molinari 1992; (3) Herbig & Jones 1983; (4) Cabrit et al. 1990; (5) Kuhi 1974; (6) Elias 1978; (7) Young, Lada, & Wilking 1986; (8) Wilking & Lada 1983; (9) Whittet 1974; (10) Jiang, Perrier, & Léna 1984; (11) Maihara, Mizutani, & Suto 1990; (12) Anthony-Twarog 1982; (13) McGregor, Persson, & Cohen 1984; (14) Staude et al. 1982.

[a] Observed 2.3 μm continuum flux. The estimated uncertainty is 10%.

[b] Excitation temperature derived from the low-resolution data. The velocity widths used are described in the text.

[c] Total optical depth of the $v = 2$–0 band head at 2.29353 μm.

[d] Total luminosity of the observed CO first overtone bands.

[e] Minimum radius of CO-emitting region, found by assuming $\tau \gg 1$. Excitation temperatures of 4000 K have been assumed for WL 16 and NGC 2024 (Geballe & Persson 1987; Carr 1989).

(Geballe & Persson 1987; Carr 1989). Since the optical depth of the 2–0 band head is indeed high for both SVS 13 and S106, these sizes indicate that the material lies within a few stellar radii of the central object.

3.2. *High-Resolution Spectra*

The high-resolution spectra in Figure 2 show considerable velocity structure, and striking differences from source to source. All the sources apart from SVS 13 show high-velocity (100–200 km s^{-1}) emission, at velocities both blue and red of the nominal band head wavelength. In DG Tau there is a dip separating the blue and redshifted emission, while in WL 16, NGC 2024 and S106 the band head is a continuous bump. SVS 13, although having optically thick emission like S106, shows very narrow lines centered on the stellar velocity.

To determine whether the profiles can be explained by accretion disks, we have produced models for the expected emission for comparison with our data. Here we give a brief summary of the results; details are presented in Paper II. The CO emission predicted from circumstellar disks originates from a region interior to the dust destruction radius, $T > 1800$ K, where the 2 μm continuum is optically thin and exterior to the region in which the temperature is high enough to dissociate CO, $T \lesssim 5000$ K. For low-mass, low-luminosity sources, this region occurs within $r \lesssim 10\ R_\odot$; for higher-mass stars it can occur between 60 and 200 $R_\odot$. Keplerian velocities at such small radii result in high-velocity profiles for the individual J-lines, with the characteristic double peaks of disk emission. As the spacing between the lines decreases close to the band head, the double-peaked profiles from adjacent J-lines overlap and beat together, resulting in spectra similar to that shown in Figure 3. The band head itself can be very broad, with its width depending upon the Keplerian velocity and the disk inclination angle. The emission is predicted to be marginally optically thick, with values for the optical depth at the $v = 2$–0 band head, τ_{2-0}, of $\sim$1–2.

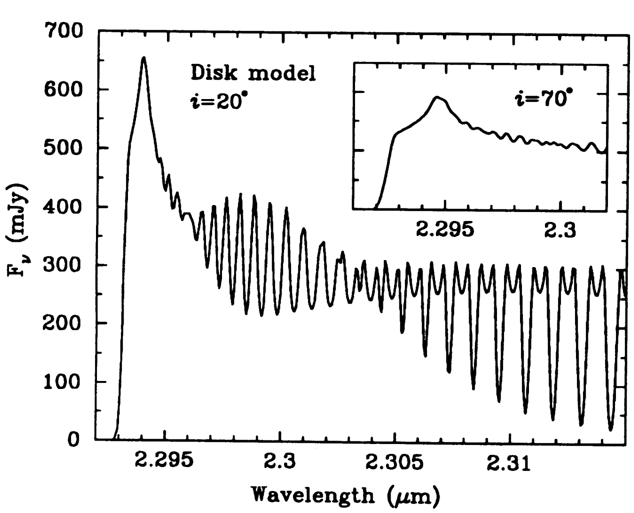

FIG. 3.—CO $v = 2$–0 band head profiles predicted by the accretion disk models described in Paper II, smoothed to 19 km s^{-1} resolution. The spectrum shown here has $M_* = 1\ M_\odot$, $R_* = 3\ R_\odot$, $T_* = 6000$ K, an inclination angle $i = 20°$, an accretion rate of $5 \times 10^{-8}\ M_\odot\ yr^{-1}$ and a distance of 350 pc. The CO emission originates from $5 < r < 15\ R_\odot$. For this inclination angle, the beating of the double-peaked lines close to the band head is clear. The inset shows the same disk for $i = 70°$, on the same wavelength scale. The shape of the band head is similar to that seen in WL 16 (Fig. 2).

3.2.1. *WL 16, NGC 2024, and S106*

WL 16, NGC 2024, and S106 all show high-velocity emission at the band head, with distinct red and blue features. The most extreme case is WL16, where the features are separated by $\sim$350 km s^{-1} (see also Dent & Geballe 1991; Carr et al. 1993). NGC 2024 and S106 both display emission $\sim$150 km s^{-1} beyond the nominal band head. These velocities are consistent with material moving at Keplerian speeds within the minimum radii listed in Table 1. Models of disk emission (Paper II) successfully reproduce the shape of the band head for all these sources, provided the disks are approximately Keplerian, and easily account for the observed fluxes. Rigidly rotating disks result in line widths too narrow to match the data.

Thompson & Januzzi (1989) found that the emission from WL 16 is optically thick based on fits to lower resolution spectra, consistent with the disk model. Furthermore, supporting evidence for the emission from S106 originating in a disk comes from the Ca II triplet at 0.85 μm (Persson, McGregor, & Campbell 1988). The excitation requirements for the triplet to be in emission are very similar to those of the CO overtone bands, and since Ca II is easily ionized to form Ca III in the presence of UV, the emission region must be well shielded. In S106, the Ca II lines are double-peaked, which Persson et al. interpret as evidence for the emitting region being a disk.

3.2.2. *DG Tau*

The emission from DG Tau displays two velocity components separated by $\sim$115 km s^{-1}, shifted symmetrically about the stellar velocity. We show in Paper II that such a double-peaked band head profile can be explained by a collimated wind. However, DG Tau is believed to have a spectral type of K7–M0, for which the CO overtone bands are seen in absorption at a level of 10%–15% of the stellar continuum (Kleinmann & Hall 1986). We have compared the spectra of standard stars in Kleinmann & Hall with our own spectra of M giants, and find that at our higher resolution the depth of the absorption is increased by $\sim$20%.

To estimate the contribution made by the photosphere to the spectrum at 2.3 μm we compare our measurements to recent models of the emission from T Tauri star/disk systems (e.g., Basri & Bertout 1989). These suggest that for DG Tau the stellar component amounts to 20%–30% of the total continuum flux, the remainder originating from a disk. We therefore estimate that the DG Tau photospheric features will be present at a level of $\sim$5% of the total continuum flux of 1.2 Jy ($\sim$60 mJy). This is in good agreement with the depth of the CO absorption feature at the nominal band head wavelength for DG Tau, indicating that the observed emission spectrum could be fitted by a disk contaminated by the stellar photosphere.

3.2.3. *SVS 13*

The lines in the $v = 2$–0 band of SVS 13 are extremely narrow and centered on the stellar velocity. A Gaussian velocity profile with a FWHM of 50 km s^{-1} fits our data well, although it tends to smear out the individual lines close to the band head which are distinct in our spectrum. Our results are in good agreement with those of Carr & Tokunaga (1992).

From the line width, it seems improbable that the CO emission from SVS 13 originates in a wind. Velocities in excess of 200 km s^{-1} relative to the stellar velocity are seen in Hα and Brγ (Eislöffel et al. 1991; Carr & Tokunaga 1992), while velocities $\gtrsim$100 km s^{-1} are detected in the $J = 1$–0 pure rotational transition within 1000 AU of the infrared source (J. Carlstrom, private communication 1993). Therefore if the rotation-vibration lines originate in a wind, it is surprising not to see velocities $\gtrsim 100$ km s^{-1}.

Carr & Tokunaga (1992) argued that the emission could not be originating from the inner region of a disk, based on the assumption that the disk inclination is constrained to be 30°–40° by the velocity vectors of the Herbig Haro objects. These inclination angles should also produce line widths of a few hundred km s^{-1}, inconsistent with the data. They suggest instead that the emission may come from a radius of ~ 1 AU. The problem then becomes one of heating the disk material to 4000 K at such a large distance from the star. We have investigated the possibility that Lyα photons from an ionized stellar wind could provide the heating mechanism (Chandler, Scoville, & Carlstrom 1993). In such a model, the depth of the CO emission region is determined by the penetration depth of the Lyα photons, which is $\sim 10^{10}$ cm. Unfortunately, this is insufficient to produce the optically thick emission seen in the low-resolution spectrum by a factor of ~ 100.

The velocity vectors of the HH objects derived from radial and proper motion studies do, however, vary from one object to the next, indicating that perhaps they are a poor measure of the disk orientation. Furthermore, the extremely high velocity cool molecular flow suggests a small inclination angle. In Paper II we attempt to model the emission from SVS 13 by a nearly face-on disk. Although the peaks of the individual *J* lines are well reproduced, the model yields line widths which are too narrow. An additional faint, broad velocity component is needed to reproduce the observed spectrum, possibly from the acceleration region of a neutral wind.

In contrast to all of the other sources for which we obtained high-resolution spectra, SVS 13 is not well fitted by a Keplerian disk model. We note, however, that if we allow our model disk to be rigidly rotating within the CO emission region, we then obtain a reasonable fit to the data, even for inclination angles as high as 40°. Both Keplerian and rigid disk models successfully account for the observed flux in the CO bands, and also predict marginally optically thick emission, consistent with the single-temperature fit derived from the low-resolution data.

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