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EMISSION FROM CO BAND HEADS IN YOUNG STELLAR OBJECTS

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ABSTRACT

Line emission from carbon monoxide at the positions of the $\Delta v = 2$ band heads has been detected in three young stellar objects (S106 IR, NGC 2024/IRS 2, GL 2789) and in MWC 349 out of 16 objects in which it has been searched for. Previously among young stellar objects, band head emission had been reported only in the Becklin-Neugebauer object and the Rho Ophiucus source, WL 16. The excitation mechanism for the CO in the new objects appears to be the same as that deduced by Scoville *et al.* for BN, i.e., collisions within a dense, hot, and compact region near the star. In at least some of the objects this region is probably a circumstellar disk.

Subject headings: infrared: sources — infrared: spectra — molecular processes — stars: circumstellar shells — stars: pre–main-sequence

I. INTRODUCTION

Scoville *et al.* (1979) detected the 2–0, 3–1, and 4–2 band heads of carbon monoxide near 2.3 μm in emission in the Becklin-Neugebauer object (BN). BN is the best known of a class of infrared-emitting objects which appear to be young and massive stars that are on or near the main sequence but are still surrounded by dense natal material as well as by molecular cloud. Scoville *et al.* (1979, 1983) show that the 2.3 μm CO line emission in BN originates in a compact region of typical dimension ~ 1 AU and with particle density greater than 10^{10} cm^{-3}. If the line-emitting gas is heated by the stellar radiation the gas must be located within ~ 1 AU of the star, yet be sheltered from intense ionizing radiation. The CO might also be shock-heated due to the interaction of a stellar wind or infalling material with circumstellar material (Scoville *et al.* 1983; Thompson 1985).

Although the infrared spectra of young stellar objects (YSOs) have been the subjects of intense observational study (e.g., Thompson 1982 and references therein; Persson *et al.* 1984), only one other detection of CO band head emission in these objects has been reported, in the low-luminosity source WL 16 (Thompson 1985), about which very little detailed information is available. If more sources of band head emission were known, one approach toward understanding the physical conditions which cause the emission would be to study it in those objects for which a variety of information is already available. Thus it is of interest simply to learn how common the phenomenon is in YSOs. With these points in mind and as a first step, we have made a search for CO band head emission at 2.3 μm in 16 diverse objects which are either YSOs or whose spectral characteristics bear some resemblance to them. No attempt was made to make a systematic survey, and indeed the luminosities, obscurations, and mass-loss rates of these objects vary over a considerable range. Many of these objects have been observed previously at high spectral resolution near 2.3 μm with no claimed detections of CO line emission. However, more sensitive searches for the CO band heads are now possible with modest integration times. Four of the objects observed in this search were found to have line emission at the CO band heads.

II. OBSERVATIONS AND RESULTS

Spectra were obtained between 2.27 μm and 2.38 μm at the United Kingdom Infrared Telescope on Mauna Kea. The facility cooled grating spectrometer (Wade 1983) was used with its 637 lines per mm grating in first order. Measurements were made between 1984 November and 1985 July; an observing log is given in Table 1. BN was the only previously known source of CO band head emission to be observed. During all measurements a 5″ diameter aperture was employed and the chopper throw was $\sim 30''$. Flux calibration and correction for telluric absorption were obtained by dividing the spectrum of each source by that of a nearby, bright star of known K magnitude and of spectral type earlier than G0 (so that CO absorption in the stellar atmosphere did not cause confusion) and multiplying by the blackbody spectral intensity corresponding to the stellar temperature. The resultant spectra of all 17 sources are displayed in Figure 1. The original spectra were fully sampled; in Figure 1 the spectra are Hanning-smoothed and the resolution is ~ 0.0035 μm (~ 7 cm^{-1}). This resolution is not high enough to resolve individual CO lines from each other, even far from the band heads. The wavelengths of the 2–0, 3–1, 4–2, and 5–3 band heads of $^{12}C^{16}O$ are 2.294 μm, 2.323 μm, 2.352 μm and 2.383 μm, respectively, and are indicated in the figures.

The flux calibrations are thought to be accurate to $\pm 20\%$. For all sources observed except GL 2789 the continuum flux density in Figure 1 is consistent with that from previously published broad-band photometry. GL 2789 was observed on two occasions, which gave the consistent result that the continuum flux in a 5″ diameter aperture is approximately one-half that reported by Harvey and Lada (1980) and by Humphreys, Merrill, and Black (1980), who used 8″ and 9″ apertures, respectively. Either the source has varied substantially over a period of 5 yr, or it is extended at infrared wavelengths. Lebofsky *et al.* (1976) measured a 2.2 μm flux density which is considerably lower than ours. Humphreys, Merrill, and Black found evidence for variation of the visible spectrum over a much shorter time scale. On the other hand, the central star of GL 2789 (V645 Cygni) illuminates a small, visual reflection nebula; thus it would not be surprising if the infrared emission

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TABLE 1

OBSERVING LOG AND PARAMETERS OF CO 2–0 BAND HEAD

Source	Date Observed (U.T.)	Integration Time (s per data point)	CO 2–0 Band Head[a] Intensity (10^{-13} ergs cm^{-2} s^{-1})	Equivalent Width (μm)	(cm^{-1})	Previous Spectrum Reference
GL 2591	1984 Nov 22	32	<6	<0.0003	<0.6	1
S106/IR	1984 Nov 22, 1985 Jul 1	88	14	0.00076	1.4	2
GL 2789	1984 Nov 22, 1985 Jul 1	64	8	0.00038	0.7	3
GL 490	1984 Nov 22	48	<6	<0.00020	<0.4	1
BN	1985 Feb 7	32	22	0.00052	1.1	4, 5
OMC 2/IRS 3	1985 Feb 7	48	<2	<0.0004	<0.8	
NGC 2024/IRS 2	1985 Feb 7	32	40	0.00076	1.4	6
S235/IRS 2	1985 Feb 7	36	<3	<0.00025	<0.5	2
GL 961	1985 Feb 7	48	<1.5	<0.0005	<1.0	
R Mon	1985 Feb 7	24	<8	<0.00030	<0.6	7
GL 989	1985 Feb 7	32	<10	<0.00020	<0.4	8
T Tau	1985 Feb 7	12	<10	<0.0004	<0.7	
M8E	1985 Jul 1	40	<10	<0.00025	<0.5	
M17/IRS 1	1985 Jul 1	36	<2	<0.0004	<0.7	9
W51/IRS 2	1985 Jul 1	96	<1.5	<0.0008	<1.5	10
P Cygni	1985 Jul 1	8	<25	<0.00015	<0.3	
MWC 349	1985 Jul 1	16	63	0.00041	0.8	11

[a] CO fluxes measured over a 0.016 μm (30 cm^{-1}) wide interval centered at 2.296 μm (4355 cm^{-1}).

REFERENCES.—(1) Thompson and Tokunaga 1979*b*; (2) Tokunaga and Thompson 1979*b*; (3) Harvey and Lada 1980; (4) Scoville *et al.* 1979; (5) Scoville *et al.* 1983; (6) Thompson, Thronson, and Campbell 1981; (7) Thompson and Tokunaga 1979*a*; (8) Thompson and Tokunaga 1978; (9) Tokunaga and Thompson 1979*a*; (10) Thompson and Tokunaga 1980; (11) Thompson *et al.* 1977.

were extended over several arc seconds. Additional photometry as well as small beam mapping are required to resolve this issue.

CO band heads were detected in emission in five sources (S106 IR, NGC 2024/IRS 2, MWC 349, GL 2789, and BN). Of these the first four are new detections. No band head emission was found in M17/IRS 1, W51/IRS 2, S235/IRS 2, OMC 2/IRS 3, M8 E/IR, GL 490, GL 961, GL 989, GL 2591, R Mon, T Tauri, or P Cygni. Absorption due to the CO band heads was not detected in any source. Measured 2–0 band head intensities and equivalent widths are given in Table 1. The equivalent width found for BN is consistent with that measured by Scoville *et al.* (1983). Spectra of those objects in which the band heads were detected are shown in more detail in Figure 2. In this figure a linear baseline has been subtracted from the spectrum of each object. It can be seen that the most intense CO band heads, in NGC 2024/IRS 2 and in MWC 349, are roughly 2 and 3 times, respectively, as bright as those in BN. The band heads in S106 IR are approximately two-thirds as intense as those in BN and those in GL 2789 approximately one-third as intense. The equivalent widths of the band heads are highest in NGC 2024/IRS 2 and S106 IR, roughly 1.5 times higher than those in BN. Emission to long wavelength of each band head is also apparent in most objects; this emission comes from unblended CO lines [see the high resolution spectrum in Scoville *et al.* (1983)]. Emission at the ^{13}CO band heads is not apparent in any source. An unidentified line is present in MWC 349 at 2.348 μm ($\sim$4260 cm^{-1}), near the position of the 2–0 band head of ^{13}CO and partially blended with the 4–2 band head of ^{12}CO. A bright unidentified line at 4256 cm^{-1} also appears in the high-resolution spectrum of MWC 349 obtained by Hamann and Simon (1986) and has not been reported in any other object. No lines other than CO are apparent in any other source at this spectral resolution.

The newly detected CO band head emission in two of these objects may also be present in previously published spectra. The 2–0 band head of ^{12}CO in NGC 2024/IRS 2 appears to be present at the several sigma level in the spectrum of Thompson, Thronson, and Campbell (1981), but was not mentioned by them. The spectrum of S106 IR by Tokunaga and Thompson (1979*b*) shows CO band heads in emission at approximately the strengths measured here; however, the emission was ascribed to CO in absorption in the comparison star.

III. ANALYSIS AND DISCUSSION

The five luminous sources which were found to have CO $\Delta v = 2$ emission range from highly obscured objects of the BN type (BN, NGC 2024/IRS 2) to moderately obscured (S106 IR) and optically bright (GL 2789, MWC 349) objects for which red and near-infrared spectroscopy has recently been shown to be fruitful (McGregor, Persson, and Cohen 1984). Because of these differences in extinction, differences in apparent brightness, and the related varying quantities and qualities of data available for each object, it is difficult to find appropriate means of comparison. Thus discussion must be highly speculative at this stage.

a) CO *Temperatures and Densities*

For those stars in which band head emission was detected, the CO excitation temperatures may be derived from comparisons of the intensities of the different band heads, if it is assumed that the band heads are optically thin. This assumption cannot be proved from the present low-resolution data, but is correct for both BN and WL 16 (Scoville *et al.* 1983; Thompson 1985). The excitation temperatures for NGC 2024/IRS 2 and S106 IR are both $\sim$4000 K, similar to the temperatures found for BN and WL 16. The derived temperature of the CO in MWC 349 is probably $\sim$3500 K (there is uncer-

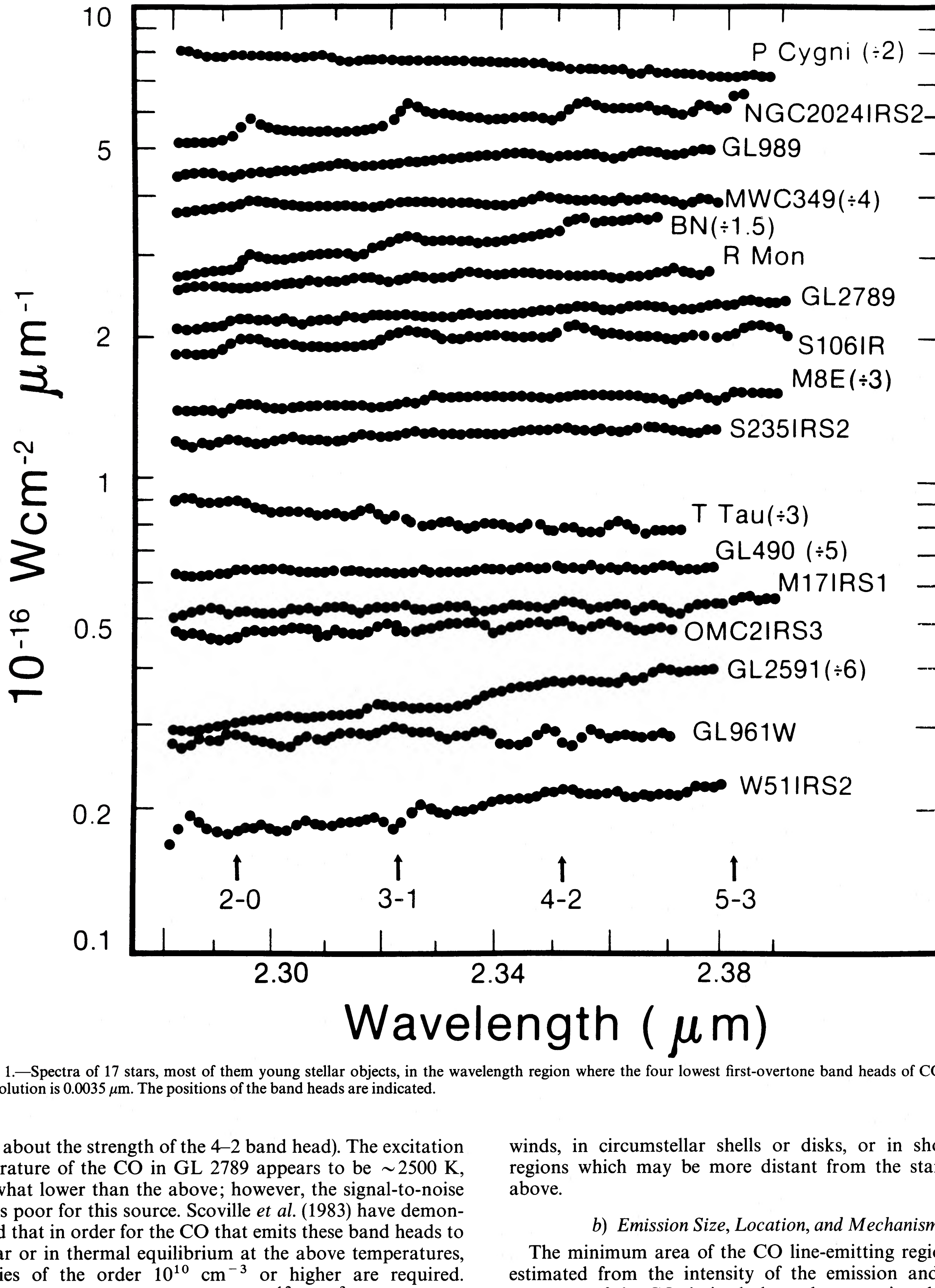

FIG. 1.—Spectra of 17 stars, most of them young stellar objects, in the wavelength region where the four lowest first-overtone band heads of CO are located. The resolution is 0.0035 μm. The positions of the band heads are indicated.

tainty about the strength of the 4–2 band head). The excitation temperature of the CO in GL 2789 appears to be $\sim$2500 K, somewhat lower than the above; however, the signal-to-noise ratio is poor for this source. Scoville *et al.* (1983) have demonstrated that in order for the CO that emits these band heads to be near or in thermal equilibrium at the above temperatures, densities of the order 10^{10} cm^{-3} or higher are required. Thompson estimates densities of $\sim 10^{12}$ cm^{-3} for the band head emitting region in WL 16. Such temperatures and densities are possible in extended stellar atmospheres, in dense winds, in circumstellar shells or disks, or in shock-heated regions which may be more distant from the star than the above.

b) Emission Size, Location, and Mechanism

The minimum area of the CO line-emitting region may be estimated from the intensity of the emission and the temperatures of the CO derived above, by assuming that the CO lines near the band head are optically thick. This has been done by using current estimates of the extinction and distances

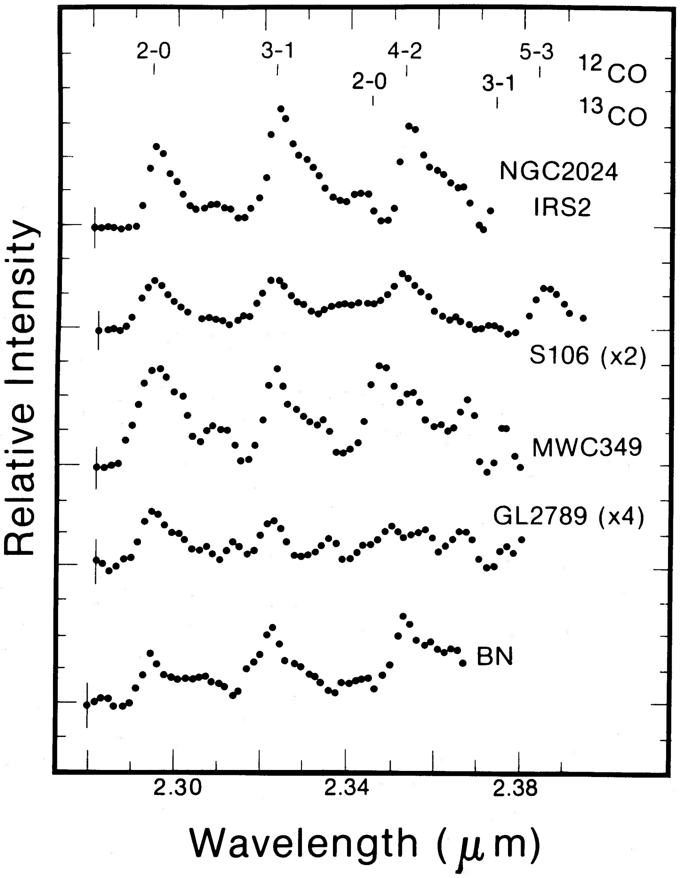

FIG. 2.—Spectra of those sources in which CO band head emission was detected. Linear baselines have been subtracted from each spectrum. The positions of the band heads are indicated at the top of the figure. Vertical scale marks are separated by 2×10^{-17} W cm^{-2} μm^{-1}. Noise levels are indicated on the short wavelength data points.

to the objects and with the additional assumptions that the lines are 50 km s^{-1} wide and do not overlap. The results are shown in Table 2. The results demonstrate that even if the areas are circles, corresponding to a spherically symmetric emission regions, in all cases their dimensions are significantly (~2–10 times) larger than the radii of ZAMS central stars as derived from total luminosity and ionization arguments. If the CO lines arise from an nonspherically symmetric region such as a disk, and/or are optically thin, as seems likely, the CO line emission arises at distances of the order of 1 AU from the star. Scoville *et al.* (1979) and Thompson (1985) have arrived at similar conclusions for the cases of BN and WL 16.

Table 2 is also an intercomparison of spectral features of these stars which may be related to conditions causing the band head emission. Although the table is not complete it can be seen that many of these objects possess common characteristics. The most obvious of these is the presence of recombination lines of atomic hydrogen in emission. This common characteristic is not surprising, given that of the 17 objects observed, H I lines are not detected in only two of them (GL 2591 and OMC 2/IRS 3). The presence of H I lines in emission implies that there are regions above the stellar photosphere which are probably too hot for CO to survive. In four of the six sources (BN, S106 IR, NGC 2024/IRS 2, and MWC 349) H I line profiles have been measured, and in all four they are broad (FWZI $\gtrsim$ 200 km s^{-1}). In the first three of these the broad lines are thought to originate in high-velocity outflowing winds (e.g., see Persson *et al.* 1984); in MWC 349 a combination of rotation and outflow is suspected (Hamann and Simon 1986). In BN, the only object for which high-resolution spectroscopy of the band head region has been obtained (Scoville *et al.* 1983), the individual CO overtone line widths are considerably narrower than the H I line widths, thus demonstrating, at least for this source, that the regions of H I line emission and CO line emission cannot be one and the same. This is also likely to be true for the other sources with ionized winds. For WL 16, where the Brγ (2.17 μm) line is much weaker with respect to the band heads than in any of the sources with ionized winds, Thompson (1985) has modeled and H I and CO line emission as originating in the same circumstellar region.

Another feature which many of the sources are known to have in common is emission from low-excitation atomic lines. Scoville *et al.* (1983) found lines of Na I and Fe II in the 2 μm spectrum of BN. McGregor, Persson, and Cohen (1984) have detected the Ca II near-infrared triplet and other low-excitation lines in the near-infrared spectra of S106 IR, GL 2789, and MWC 349. Both sets of authors conclude that these atomic lines must arise in regions which are at least moderately dense, have temperatures of only a few thousands of degrees, and are

TABLE 2

CHARACTERISTICS OF SOURCES SHOWING INFRARED CO LINE EMISSION

Source Name	Distance (Kpc)	2.3 μm Extinction (mag)	CO Temperature (K)	Minimum Area of CO Band Head Region (10^{24} cm^2)^a	H I Lines Detected?	Low-Excitation Atomic Lines Detected?	Molecular Outflow: Observed Nearby? (mm)	Molecular Outflow: From This Source (i.r.)	Reference
BN	0.50	3.5	4000	13	Y, broad	Y	Y	N	1, 2
S106IR	0.60	1.3	4000	1.5	Y, broad	Y	Y	...	3, 4, 5
NGC 2024/IRS 2	0.50	1.2	4000	2.8	Y, broad	...	Y	N	6, 7, 8, 9
GL 2789	6.0	0.4	2500	100	Y, ...	Y	Y	...	4, 5, 9
MWC 349	1.2	1.0	3500	25	Y, broad	Y	...	...	10, 11
WL 16	0.15	7.5	4000	10	Y, ...	...	N	...	12, 13

[a] Derived from band head intensities in Table 1 using the distances and extinction to the sources as given in the references (with $A_{2.3\,\mu m} = 0.1 A_v$), the CO temperatures given in this paper and in the references, and with the assumption that the individual CO lines are optically thick, 50 km s^{-1} wide, and unblended.

REFERENCES.—(1) Scoville *et al.* 1983; (2) Kwan and Scoville 1976; (3) Persson *et al.* 1984; (4) McGregor, Persson, and Cohen 1984; (5) Bally and Lada 1983; (6) Thompson, Thronson, and Campbell 1981; (7) Geballe, Smith, and Fischer 1986; (8) Black and Willner 1984; (9) Harvey and Lada 1980; (10) Thompson *et al.* 1977; (11) Hamann and Simon 1986; (12) Thompson 1985; (13) Wilking and Lada 1983.

distant and well-shielded from the ultraviolet flux of the central star. At least superficially, these conditions resemble those required for CO first-overtone line emission.

One cannot directly compare emission in the CO band with that in a low-ionization species such as Ca II in the 8000 Å region, because the objects are so severely reddened. If, however, it is assumed that the H I lines in these objects are emitted from regions whose overall physical conditions and geometries are similar (e.g., from stellar winds; Krolik and Smith 1981; Persson *et al.* 1984), meaningful comparisons can be made between ratios of the low-excitation features to nearby H I lines. Using Brγ line strengths in the literature and the near-infrared spectra of McGregor, Persson, and Cohen (1984), we have compared the intensity ratio of the CO 2–0 band head relative to Brγ with that of Ca II at 8542 Å relative to Pa 12 at 8750 Å. The comparison indicates that if CO band emission is seen, then Ca II lines are also seen (if the object can be observed at all at 8500 Å—BN and NGC 2024/IRS 2 cannot). On the other hand, there are objects in which Ca II is very intense but CO band emission is not seen–T Tau (S. E. P., unpublished data) and possibly GL 989 are such examples. For some of the observed sources (e.g., GL 490) the present upper limit to the CO band emission relative to Brγ is not interesting. We conclude on the basis of the present very scanty information that there is no direct correlation between the strengths of the emission lines of CO and Ca II. Because the physical conditions deduced for the excitation of these lines are similar, it may be that other differences, such as geometry, are important in the line production. The velocity profiles of individual CO and Ca II lines may shed further light on their relationship.

Not surprisingly, most of the band head emission sources are located near molecular outflows, which have been observed primarily in CO millimeter and submillimeter lines (e.g., Bally and Lada 1983). However, one source (WL 16) does not have a flow associated with it (Wilking and Lada 1983). No data are available on a second source, MWC 349, but its relatively small extinction (Herzog, Gehrz, and Hackwell 1980) suggests that no molecular flow is present. For those band head emission sources which are located near molecular flows it has not been possible to identify the flow seen in millimeter lines specifically with activity near the star, as, for example, has been done in the case of the source GL 2591 (Geballe and Wade 1985) via infrared absorption spectroscopy of CO. This does not necessarily imply that the outflow does not originate from the source, as its orientation is critical for its detection in absorption lines. It also should be noted that the detection of infrared CO and H I emission lines from a star is difficult if a massive molecular outflow, producing high extinction, is present along the line of sight. However, the examples of WL 16 and MWC 349 indicate that molecular outflows are not a necessary ingredient in the production of CO band head emission.

Based on all of the above one might conclude hesitantly that two characteristic regions are always present in sources showing CO band head emission. One of these is a region of ionized gas, which often, and perhaps always, is in the form of a stellar wind. Given the bias of the present survey toward emission-line objects, it is perhaps only significant that a wind seems to be required. The second is a dense, largely neutral region outside the star, characterized by low-excitation atomic line emission. It is also fairly clear, except perhaps in the case of WL 16, that the CO band head emission must originate in circumstellar material, rather than in an extended photosphere, and that, despite the lack of correlation between CO band head and low-excitation atomic line strengths, they must be physically linked.

Although there is little direct evidence to demonstrate that a single physical mechanism accounts for the line emission by CO at 2.3 μm in all sources in which it has been detected, it is tempting to search for one. In BN and in the four objects detected in this study it appears that direct stellar radiation could provide sufficient energy input for the line emission. However, if the extent of the line-emitting region around the low-luminosity star, WL 16, is as large as that proposed by Thompson (1985), its CO cannot be directly heated by stellar radiation. A second possibility for CO excitation is shock-heating. The detections of band head emission in relatively unobscured stars, in particular MWC 349, imply that the emission does not usually occur during the protostellar phase, due, for example, to a accretion shock caused by infalling matter. Thus, if the common emission process is a shock phenomenon, it must involve outflowing material (a partially or fully ionized wind in these cases). Circumstellar disks,which for a number of independent reasons are thought to exist in several of the band head sources, provide regions where a high-velocity outflow can cause a shock in high-density neutral material. Scoville *et al.* (1983) concluded that a rotating disk could not be the location for the observed narrow CO emission lines in BN unless the disk is seen nearly face-on. However, as pointed out by Thompson (1985), shocked disk material may have a lower rotational velocity than the rest of the disk. Future velocity-resolved observations of individual 2.3 μm CO lines in several sources, as well as similar observations of other emission lines, will provide tests of the above models.

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REFERENCES

Bally, J., and Lada, C. J. 1983, *Ap. J.*, **265**, 824.
Black, J. H., and Willner, S. P. 1984, *Ap. J.*, **279**, 673.
Geballe, T. R., Smith, H. A., and Fischer, J. 1986, in preparation.
Geballe, T. R., and Wade, R. 1985, *Ap. J.* (*Letters*), **291**, L55.
Hamann, F., and Simon, M. 1986, *Ap. J.*, **311**, 909.
Harvey, P. M., and Lada, C. J. 1980, *Ap. J.*, **237**, 61.
Herzog, A. D., Gehrz, R. D., and Hackwell, J. A. 1980, *Ap. J.*, **236**, 189.
Humphreys, R. M., Merrill, K. M., and Black, J. H. 1980, *Ap. J.* (*Letters*), **237**, L17.
Krolik, J. H., and Smith, H. A. 1981, *Ap. J.*, **249**, 628.
Kwan, J., and Scoville, N. Z. 1976, *Ap. J.* (*Letters*), **210**, L39.
Lebofsky, M. J., Kleinmann, S. G., Rieke, G. H., and Low, F. J. 1976, *Ap. J.* (*Letters*), **206**, L157.
McGregor, P. J., Persson, S. E., and Cohen, J. G. 1984, *Ap. J.*, **286**, 609.
Persson, S. E., Geballe, T. R., McGregor, P. J., Edwards, S., and Lonsdale, C. J. 1984, *Ap. J.*, **286**, 289.
Scoville, N. Z., Hall, D. N. B., Kleinmann, S. G., and Ridgway, S. T. 1979, *Ap. J.* (*Letters*), **232**, L121.
Scoville, N. Z., Kleinmann, S. G., Hall, D. N. B., and Ridgway, S. T. 1983, *Ap. J.*, **275**, 201.
Thompson, R. I. 1982, *Ap. J.*, **257**, 171.
———. 1985, *Ap. J.* (*Letters*), **299**, L41.

Thompson, R. I., Strittmatter, P. A., Erickson, E. E., Witteborn, F. C., and Strecker, D. W. 1977, *Ap. J.*, **218**, 170.
Thompson, R. I., Thronson, H. A., and Campbell, B. G. 1981, *Ap. J.*, **249**, 622.
Thompson, R. I., and Tokunaga, A. T. 1978, *Ap. J.*, **226**, 119.
———. 1979*a*, *Ap. J.*, **229**, 153.
———. 1979*b*, *Ap. J.*, **231**, 736.
Thompson, R. I. 1980, *Ap. J.*, **235**, 889.
Tokunaga, A. T., and Thompson, R. I. 1979*a*, *Ap. J.*, **229**, 583.
———. 1979*b*, *Ap. J.*, **233**, 127.
Wade, R. 1983, *Proc. Soc. Photo-Opt. Instr. Eng.*, **445**, 47.
Wilking, B. A., and Lada, C. J. 1983, *Ap. J.*, **274**, 698.

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