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FIRST-OVERTONE CO VARIABILITY IN YOUNG STELLAR OBJECTS[1]

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ABSTRACT

We have monitored the 2.3 μm $\Delta v = 2$ CO bands toward young stellar objects that are predominantly of low luminosity ($L < 10{,}000\ L_\odot$) and show evidence of mass loss. The CO emission can be highly variable, on timescales as short as a few days. In DG Tau, the bands have been observed to disappear and reappear and may also have a periodic modulation. For the BN object, the equivalent width has varied by a factor of 3; and for V1331 Cyg, the equivalent width doubled in 9 days. Changes in equivalent width also occurred in SSV 13, AS 353A, and 1548C27, while WL 16 and S106 have not shown variations.

Of the nine CO absorption sources reobserved, only the FU Ori–type star V1057 Cyg went through a significant change in equivalent width. It also presents an unusual and variable band profile.

Subject headings: infrared: stars — stars: pre–main-sequence

1. INTRODUCTION

One of the most powerful ways of probing the physical conditions of the hot (1000–6000 K) and dense ($n_{\rm H} > 10^{10}$ cm^{-3}) neutral gas regions around young stars is high-resolution infrared spectroscopy of vibrationally excited molecular radiation, such as the first-overtone CO band heads. Following the first discovery of CO band head emission by Scoville et al. (1979) in the BN object, many young stellar objects (YSOs) have been found to have CO first-overtone emission or absorption (Geballe & Persson 1987; Carr 1989). A number of mechanisms for producing CO emission have been proposed over the years.

One of the first suggestions was that the emission originates from neutral stellar or disk winds (Carr 1989; Chandler et al. 1993; Chandler, Carlstrom, & Scoville 1995), with the CO-band luminosity depending on the mass-loss rate and velocity of the wind. Carr (1989) and Chandler et al. (1995) showed that the observed CO-band profiles and luminosities can be reproduced by disk models with mass-loss rates of 10^{-7} to $10^{-5}\ M_\odot$ yr^{-1}, wind velocities of ~ 200 km s^{-1}, and temperatures of 3000–4000 K. Variations in the CO could result from instabilities in these winds. The inner circumstellar disk regions were also considered as a possible source (Najita et al. 1996 and references therein). Calvet et al. (1991) have shown that for a young star irradiating onto an optically thick accretion disk the CO behavior depends on a balance between the disk's surface temperature, generated by the central object, and effective temperature, generated by the accretion process. Thus, CO bands originating in the inner disk regions will appear in emission if the accretion rate is relatively low and the stellar radiation creates a hot surface layer. For high accretion rates the CO bands will appear in absorption, because the internal heat of the disk dominates the radiation transfer. In this model changes in the CO bands might indicate variations in accretion rate. Alternatively, high accretion rates may lead to a significant increase of UV radiation at the accretion shock that in turn will heat the surface layer of the disk, thereby favoring CO emission rather than absorption. Variations would also result if the structure of the disk changes, particularly in the ~ 0.1 AU radius region where CO emission arises.

Magnetic accretion models have been explored, where the inner disk is disrupted by the field lines and the material is funneled onto the star (Königl 1991; Shu et al. 1994). Recently, Martin (1997) proposed that the CO emission may arise in the infalling material, rather than in the inner regions of the circumstellar disk. The infalling gas is heated by adiabatic compression from 3000 K at the base of the flow to ~ 6000 K in the inner regions, and the CO originates in the regions of $T < \sim 5000$ K. Martin shows that high-resolution band profiles are satisfactorily reproduced by T Tauri star parameters and a plausible inclination of the disk to the line of sight. The CO flux is proportional to the accretion rate. The collimated flow will also produce magnetic hot spots, so rotationally modulated photometric variations are to be expected at optical and infrared wavelengths, along with CO flux variations.

Photometric variations in a significant number of T Tauri stars (some of which show CO emission) have been observed (Bouvier et al. 1993, 1995; Skrutskie et al. 1996), with periodic (1.2–24 days) as well as nonperiodic components. Although CO-band variations are a possibility in all the models discussed above, such effects have not been investigated systematically to date. This paper explores the variability in CO first-overtone bands to determine the prevalence of such behavior, to test its relation to other aspects of YSOs, and to set the stage for future, more detailed studies. We have found CO emission to be highly variable with timescales of months or even days.

2. NEW OBSERVATIONS

Our observations were obtained with FSpec (Williams et al. 1993) on the Steward Bok Telescope (2.3 m) during 1995 January 21–23 (UT) and 1996 September 2–3 (UT), and on the Multiple Mirror Telescope (MMT) during 1996 June 3–7 and December 21–31 (UT). FSpec is a long-slit spectrometer using a 256 × 256 near-infrared camera and multi-object spectrometer (NICMOS3) detector array. On the Bok Telescope, the pixels are projected to 1″.2 square and the slit is 2″.4 wide by 96″ long. On the MMT, the pixels are 0″.43 and the slit is 1″.2 wide by 32″ long. The sources were placed on the slit using an IR camera guiding off the slit,

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and spectra were obtained in sets of four or six by moving the telescope between integrations so the sky could be removed by subtracting adjacent spectra taken along the slit. The observations used 600 groove mm^{-1} and 300 groove mm^{-1} gratings, and gave resolving powers ($\lambda/\Delta\lambda$) of approximately 7400 and 2700 $pixel^{-1}$, respectively. Since the slit is ~ 2 pixels wide, the achieved resolution is 2–2.5 times lower than the per pixel value.

Measurements of solar- and A-type standards close on the sky to each object were interspersed with the YSO measurements every 20 minutes or less to allow accurate correction for terrestrial atmospheric absorption. Data were obtained under both photometric and nonphotometric conditions; in the former case, experience with the spectrometer in this configuration indicates that the source continuum brightness should be measured relative to the standard to an accuracy of about 30%. During the December telescope run when three sources were intensively monitored, the seeing was quite constant at $\leq 1''$, so variable slit losses are unlikely to contribute abnormally large uncertainties. Where conditions are nonphotometric we cannot quote a continuum level, but the equivalent widths of the CO features should still be accurate.

3. DATA REDUCTION

The data were reduced using both IRAF routines and scripts written specifically for FSpec. From each image a background consisting of the average of the images taken before and after was subtracted. This process removed the sky background as well as the dark current. Dark-current–corrected images of a uniformly illuminated blank screen were used to flat-field the data. A mask was used to mark bad pixels and remove them in further processing. The wavelengths were calibrated using sky lines of OH or a NeKr comparison lamp. Atmospheric absorption was corrected by dividing with a spectral reference observation (F6–G3-V star) obtained at the same air mass immediately before or after each object integration. The spectra were then multiplied by a normalized flat solar spectrum to remove artifacts caused by features in the standard star spectrum (Maiolino, Rieke, & Rieke 1996), and by a blackbody of the standard star's temperature to restore the slope. Comparison with the same spectra divided by A-type stars, which have few lines in this spectral region, confirmed that none of the features in the final spectrum were introduced by this process. Flux calibration used the V magnitude and nominal $V-K$ colors of the spectral reference star (Johnson 1966) to obtain its flux at 2.2 μm, which was then extrapolated to the flux at 2.3 μm assuming a Rayleigh-Jeans spectrum.

4. RESULTS

4.1. *CO Emission Sources*

The results for the nine sources in which Carr found CO bands in emission are given in Tables 1 and 2. Table 1 compares Carr's data and our data taken in 1995 January, 1996 June, and 1996 September. This table gives a coarse description of variability with time, since the spectra were taken at least 3 months apart. Table 2 shows similar data for DG Tau, SSV 13, and V1331 Cyg, but taken over several nights, 1996 December 21–31 (UT), thus representing a more detailed monitoring with time. To compare with Carr's data we use the ratio $R = F_{CO}/S_{2.3}$ (Tables 1 and 2, col. [3]), where F_{CO} is the integrated CO (2–0) band flux as defined by Carr (1989), and $S_{2.3}$ is the continuum flux at 2.3 μm, measured from a linear continuum fitted shortward of 2.29 μm. This ratio, computed from the spectra prior to flux calibration, provides a reliable comparison of our

TABLE 1

CO BAND HEAD EMISSION

Object	UT Date	$F_{CO}/S_{2.3}$[a] (10^{10} Hz)	$S_{2.3}$[b] (Jy)
SSV 13	1986[c]	20	0.12
	1995 Jan	21.8	Nonphotometric
	1996 Sep	21.32	0.43
DG Tau	1986[c]	6.69	1.3
	1995 Jan	1.11	Nonphotometric
	1996 Sep	16.53	Nonphotometric
WL 16	1986[c]	28.98	0.49
	1996 Jun	30.8	0.49
AS 353A	1986[c]	11.43	0.56
	1996 Jun	4.73	0.39
	1996 Sep	5.22	0.30
1548C27	1986[c]	14.28	0.35
	1996 Jun	25.8	0.39
	1996 Sep	29.95	0.73
V1331 Cyg	1986[c]	25.71	0.28
	1996 Jun	22.68	0.23
	1996 Sep	25.32	0.29
Bn object	1986[c]	5.11	7.9
	1996 Sep	15.27	9.49
	1996 Dec 28	10.81	10.13
S106	1986[c]	5.54	3.5
	1996 Jun	5.32	4.33
	1996 Sep	5.87	3.55
S140 IRS 1	1986[c]	2.21	1.9
	1996 Jun	[d]	1.50
	1996 Sep	[d]	4.92

[a] F_{CO}: Integrated CO (2–0) band flux from 2.293 to 2.317 μm, above linear continuum. $S_{2.3}$: Flux at 2.3 μm extrapolated from linear continuum fitted shortward of 2.29 μm (see text).

[b] $S_{2.3}$: Continuum flux at 2.3 μm computed using standard star's V magnitude and $V-K$ color.

[c] Carr 1989.

[d] Not detected (see text).

TABLE 2

CO BAND HEAD EMISSION: DAILY MONITORING

Object (1)	UT Date (2)	$F_{CO}/S_{2.3}$[a] (10^{10} Hz) (3)	$S_{2.3}$[b] (Jy) (4)
DG Tau	1996 Dec 21	18.91	Nonphotometric
	1996 Dec 22	15.95	Nonphotometric
	1996 Dec 23	11.14	1.24
	1996 Dec 24	13.20	1.26
	1996 Dec 26	20.69	1.13
	1996 Dec 29	14.29	Nonphotometric
	1996 Dec 31	14.63	1.45
SSV 13	1996 Dec 22	13.85	Nonphotometric
	1996 Dec 23	6.68	0.77
	1996 Dec 24	11.90	0.57
	1996 Dec 26	18.13	0.43
	1996 Dec 29	12.84	Nonphotometric
	1996 Dec 31	16.75	0.26
V1331 Cyg	1996 Dec 22	17.99	Nonphotometric
	1996 Dec 23	20.71	0.33
	1996 Dec 26	27.94	0.20
	1996 Dec 29	27.19	Nonphotometric
	1996 Dec 31	32.92	0.60

[a] F_{CO}: Integrated CO (2–0) band flux from 2.293 to 2.317 μm, above linear continuum. $S_{2.3}$: Flux at 2.3 μm extrapolated from linear continuum fitted shortward of 2.29 μm (see text).

[b] $S_{2.3}$: Continuum flux at 2.3 μm computed using standard star's V magnitude and $V-K$ color.

results to those of Carr (1989). To differentiate between a variation in the CO flux and a variation in the continuum flux, we present in column (4) absolute continuum fluxes at 2.3 μm, calibrated as discussed above. Figures 1, 2, and 4 display spectra of SSV 13, DG Tau, and V1331 Cyg, and show the variations in emission flux and R. The 1996 September and 1996 December spectra were taken with a resolution of ~ 1200; all earlier spectra were taken with a resolution of ~ 3700 and smoothed to 1200 for comparison.

We have the following comments on individual sources:

1. SSV 13 was observed to have brightened dramatically in late 1990 (Eislöffel et al. 1991) and was monitored in the near-infrared for the following 3 years (Aspin & Sandell 1994). Our continuum measures are consistent with or slightly brighter than the typical values measured by Aspin & Sandell (1994). Eislöffel et al. (1991) compared a CO band head spectrum with the data of Carr (1989) and concluded that the equivalent width had not changed—both continuum and band emission had increased by the same factor. Aspin & Sandell (1994) obtained four spectra and report that the equivalent width of the CO did not change between 1991 November and 1993 November. Figure 1 shows spectra of this source taken in 1995 January, 1996 September, and a series of spectra taken almost daily in 1996 December. These data are generally consistent with the behavior reported previously. However, a rapid flare of the continuum appears to have occurred on 1996 December 23 with no corresponding change in the absolute level of CO emission, as indicated by the drop in CO equivalent width. There is possibly another flare on 1996 December 29; the continuum level appears to be nearly as high as on 1996 December 23 (although conditions were nonphotometric), and the CO equivalent width is reduced from the average.

2. DG Tau has a constant continuum level within our errors, and is consistent with the level reported by Carr (1989). However, the CO equivalent width and hence the CO power show large changes. CO was fairly bright in 1986 (Carr 1989); Chandler et al. (1993) measured the same level of continuum and CO flux in 1992 September. Greene & Lada's (1996) observations of 1994 December suggest that the CO may have turned into absorption. We found the emission to be very weak, near our detection limit, in 1995

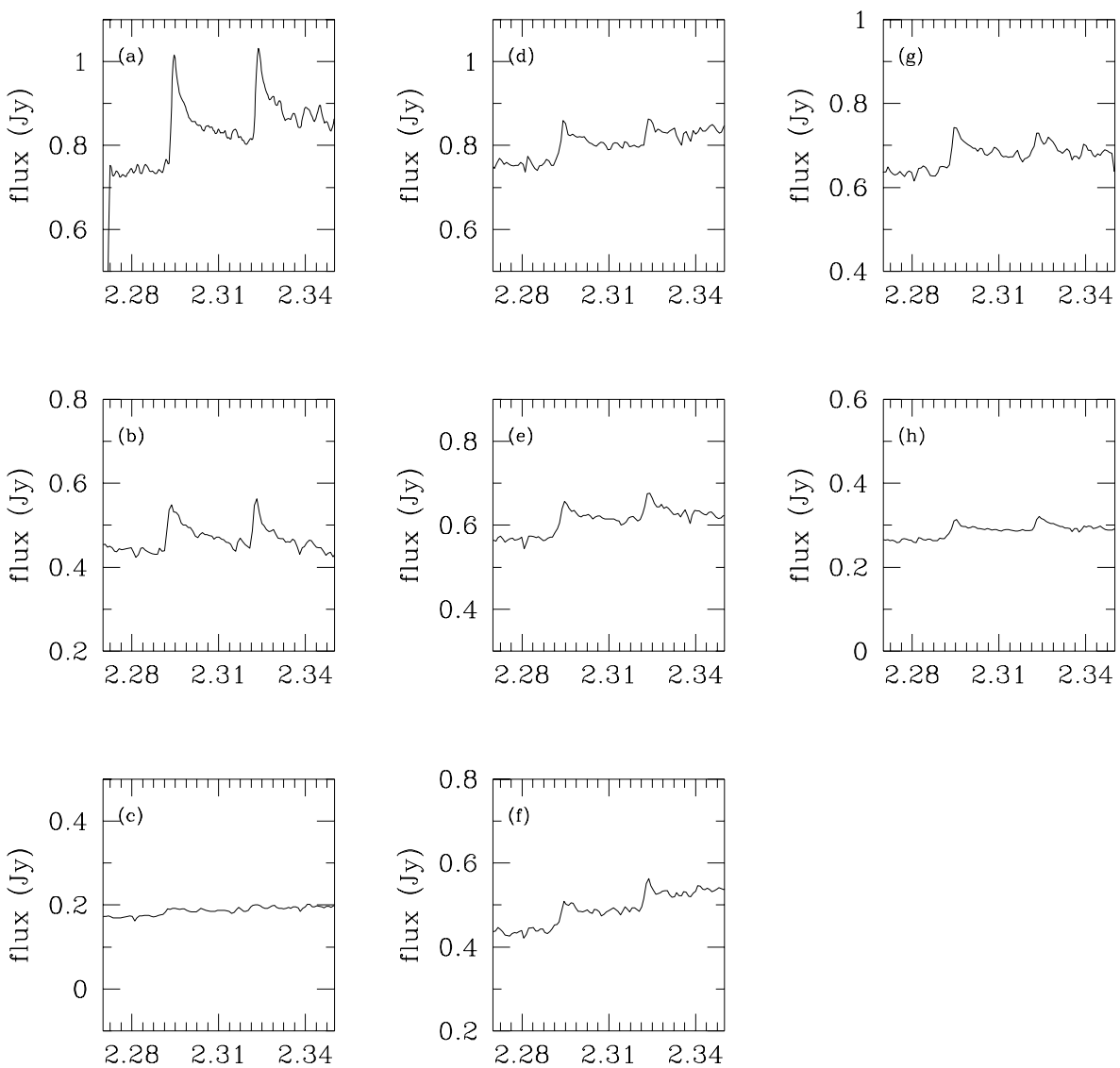

FIG. 1.—SSV 13 spectra for (*a*) 1995 January, (*b*) 1996 September, (*c*) 1996 December 22, (*d*) 1996 December 23, (*e*) 1996 December 24, (*f*) 1996 December 26, (*g*) 1996 December 29, and (*h*) 1996 December 31.

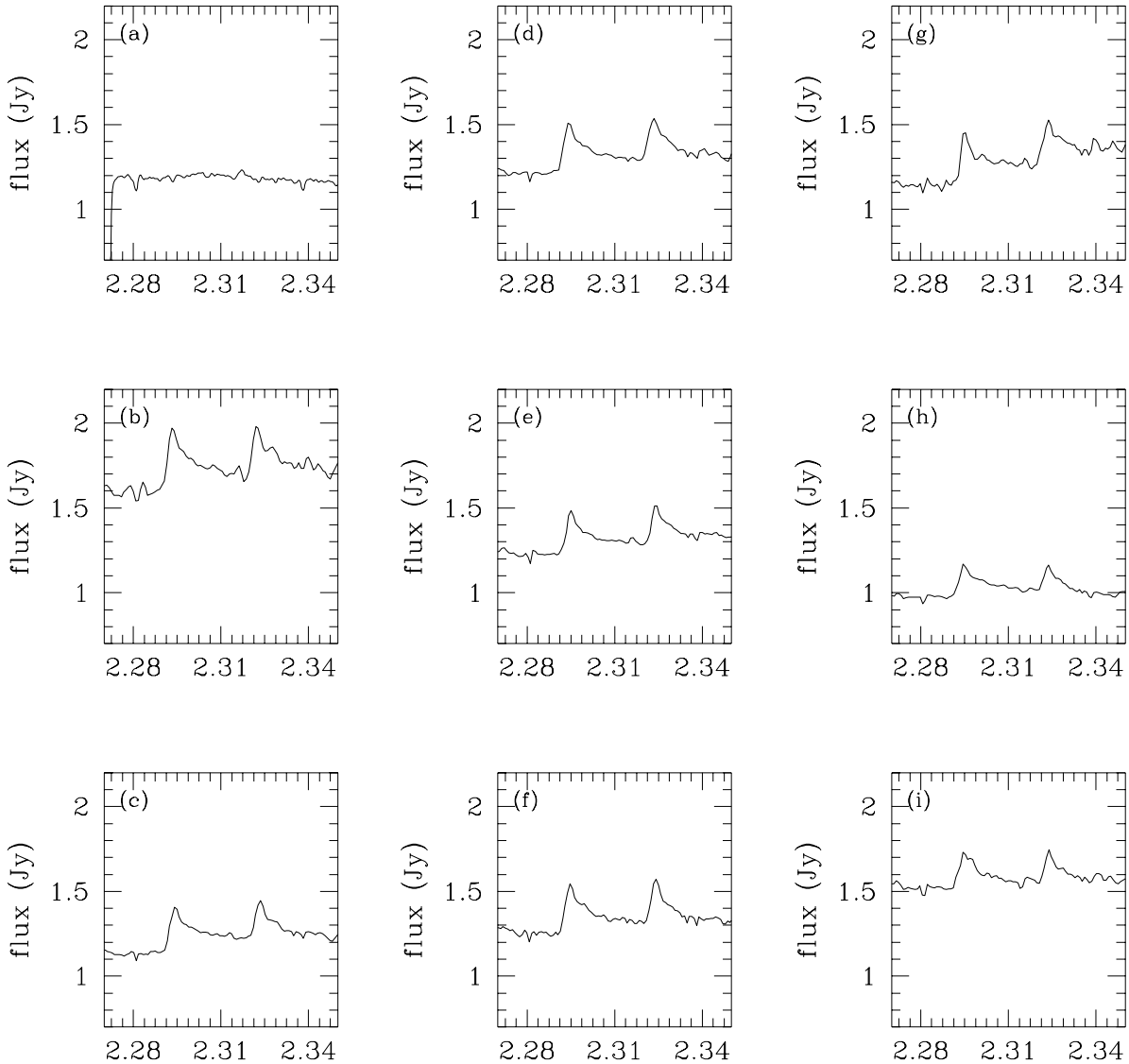

FIG. 2.—DG Tau spectra for (*a*) 1995 January, (*b*) 1996 September, (*c*) 1996 December 21, (*d*) 1996 December 22, (*e*) 1996 December 23, (*f*) 1996 December 24, (*g*) 1996 December 26, (*h*) 1996 December 29, and (*i*) 1996 December 31.

January. A. Tokunaga (1995, private communication) observed strong CO emission again in 1995 November, and our observations of 1996 September show CO emission at a very high level.

Spectra taken more frequently during 1996 December 21–31 (see Fig. 2) show that variations of nearly 50% in the ratio $R = F_{CO}/S_{2.3}$ can occur on a timescale of a few days. Bouvier et al. (1995) present a light curve for this source, obtained through V-band photometry, with an amplitude of 0.4 mag and a period of 6.3 days. These authors suggest the presence of spots slightly cooler than the photosphere (without veiling), or slightly hotter than the photosphere, with a wavelength-dependent veiling; in both cases the spots cover 15% of the surface of the star. Both spot models predict lower amplitude variations in the near-infrared than in the visible, in agreement with the absence of continuum variations in our measurements and those reported by other authors. Our CO data suggest variations with the same period (see Fig. 3).

3. WL 16 did not change within the errors since it was observed by Carr. Thompson (1985) reported a CO-to-continuum ratio in approximate agreement with these values also, although he did not obtain an independent calibration of the flux level.

4. AS 353A experienced a decrease in the CO equivalent width by a factor of 2 from 1986 to 1996; the continuum

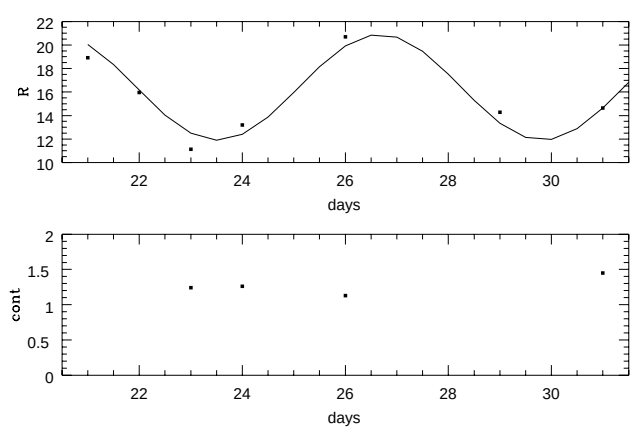

FIG. 3.—DG Tau monitoring 1996 December 21–31. *Top panel:* Ratio of CO to continuum, R. A sinusoidal curve of period 6.3 days is superimposed on the data. *Bottom panel:* Continuum at 2.3 μm.

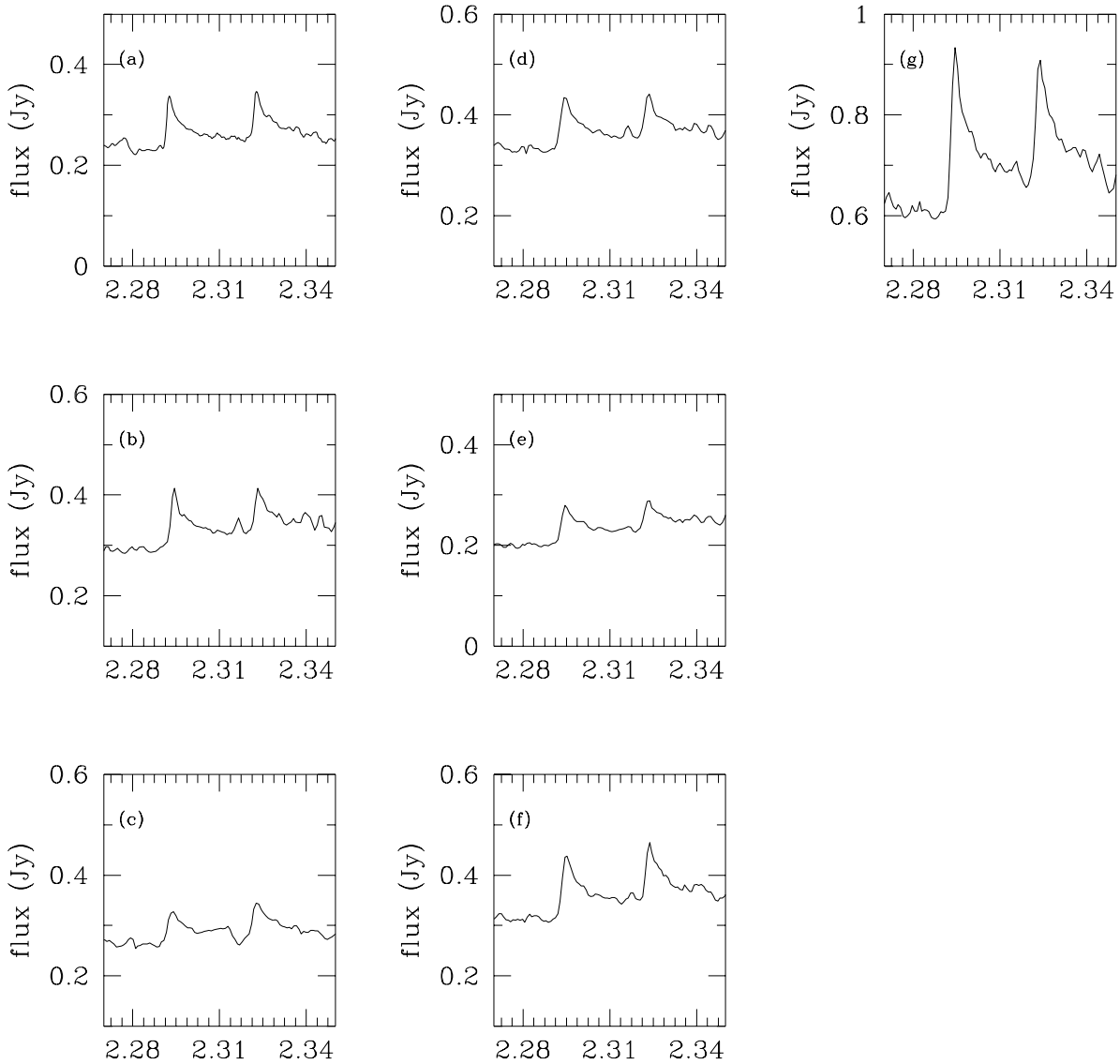

FIG. 4.—V1331 Cyg spectra for (*a*) 1996 June, (*b*) 1996 September, (*c*) 1996 December 22, (*d*) 1996 December 23, (*e*) 1996 December 26, (*f*) 1996 December 29, and (*g*) 1996 December 31.

also decreased by the same amount.

5. 1548C27 experienced a substantial increase in CO equivalent width since it was observed by Carr (1989). Its continuum also increased by a factor of about 2, perhaps between 1996 June and 1996 September (the change between these two months is at the limits of our errors for two single observations).

6. V1331 Cyg shows a steady increase in R over the 1996 December monitoring period, starting at a level below that previously observed in 1996 June and 1996 September, and ending at a much higher level on 1996 December 31 (see Fig. 4). The continuum, which had been stable over all observations including those earlier in December, rose by a factor of 2 on the same date; given the previous behavior, the existence of such flaring activity needs confirmation.

7. The BN object shows an increase of a factor of 3 in the ratio R in our observations of 1996 September, compared with those of Carr (1989). It then decreased to an intermediate level in 1996 December. Carr's results were in agreement with those reported by Scoville et al. (1983) and Geballe & Persson (1987). Within our errors, the continuum flux remains unchanged.

8. S106 remained almost constant in both $F_{CO}/S_{2.3}$ and continuum flux over our observations, which are consistent with Carr's results. The latter were also in agreement with those presented by Scoville et al. (1983) and Geballe & Persson (1987).

9. S140 IRS 1 was found by Carr to have a small CO emission equivalent width. In our data, despite higher spectral resolution and S/N, the CO emission is absent in both 1996 June and 1996 September.

A number of possibilities have been advanced to account for the CO emission in these sources. For WL 16, 1548C27, and S106, however, the line profiles strongly suggest emission in the inner zone of a circumstellar disk (Najita et al.

1996; Chandler et al. 1993). It is perhaps noteworthy that the first and third of these objects show changes in neither continuum level nor CO equivalent width. In contrast, 1548C27 shows an increase in continuum and a larger increase in CO equivalent width, indicating a change in disk structure; qualitatively, the behavior could be explained if the disk accounted for only a moderate portion of the total 2 μm emission at the time of Carr's (1989) observations, and it has now brightened to provide a larger portion without a change in the CO-to-continuum ratio for the disk alone.

The CO lines in SSV 13, V1331 Cyg, and the BN object are relatively narrow (Scoville et al. 1983; Carr & Tokunaga 1992), while DG Tau may have broad lines from a disk but a photospheric absorption feature at zero velocity, or it may have double-peaked narrow lines (Chandler et al. 1995). In these cases, it is ambiguous whether the emission is from a disk (nearly face-on for the first three sources), or a wind (Carr & Tokunaga 1992; Chandler et al. 1995). In the case of SSV 13, the variability in CO equivalent width may just be the effect of continuum variability of a source component (e.g., central star) decoupled from the CO excitation. The CO variability of DG Tau and the BN object must be intrinsic to the source region, since we detect no significant continuum variations. For DG Tau, Martin (1997) finds that the band profile observed by Chandler et al. (1993) can be explained in terms of a funnel-flow mechanism of accretion, with normal T Tauri star parameters and an accretion rate of 10^{-7} $M_{\odot}$ yr^{-1}. The funnel-flow model involves the presence of hot spots and could account for both continuum and CO periodic variations. The increase in CO equivalent width for V1331 Cyg is also not compatible with a simple dilution effect, but requires a variation in the intrinsic CO emission strength. It may be significant that the narrow-line or potential wind sources appear to have more dramatic intrinsic CO variations than do the clearest examples of disk emission; future observations should address this issue more thoroughly.

4.2. *CO Absorption*

We have obtained spectra for nine of the 12 sources in which Carr (1989) found CO absorption bands. The equivalent widths of the CO (2–0) band heads, measured from 2.293 to 2.317 μm, are shown in Table 3. The typical error in these equivalent widths, judged from the noise level in the spectra, is 1 Å.

The CO absorption equivalent width has remained constant, within our errors, for almost all of these sources; the exception to this trend is V1057 Cyg, an object of the FU Ori type. We note that the CO absorption in Haro 6-13, a class II young stellar object with spectral index $a = -0.2$, is likely to be photospheric (Casali & Eiroa 1996). The constancy of the CO absorption in the other sources suggests the presence of photospheric CO absorption in other cases also. The absorption bands in V1057 Cyg differ in shape from photospheric bands. They have changed in profile as well as in equivalent width. In Figure 5 we compare the 1996 September spectrum with a 1986 spectrum (Hartmann & Kenyon 1987). The older spectrum was taken at higher resolution, and has been smoothed to the same resolution as our spectra, $\lambda/\Delta\lambda = 3700$. The fine structure is due to R-branch transitions of the CO (2–0) and (3–1) bands. They appear in both spectra, but their equivalent widths have decreased to the point where the CO (3–1) band head is hardly noticeable in the recent spectrum. This fundamental change in the structure of the V1057 Cyg CO band heads is likely related to the optical dimming of 1995, thought to be associated with a dust condensation event in the wind from the disk (S. Kenyon 1996, private communication).

TABLE 3

CO Band Head Absorption

Object	UT Date	W_{CO}[a] (Å)
RNO 15	1986[b]	3.4 ± 0.7
	1996 Sept	3.5 ± 1
FS Tau.....	1986[b]	3.6 ± 0.4
	1995 Jan	3.3 ± 1
L1551 IRS 5.....	1986[b]	13.7 ± 1.0
	1995 Jan	10.9 ± 1
HL Tau	1986[b]	≤1.9 ± 0.8
	1995 Jan	2.6 ± 1
XZ Tau	1986[b]	≤3.1 ± 0.9
	1995 Jan	4.4 ± 1
Haro 6-13	1986[b]	4.0 ± 0.4
	1995 Jan	2.7 ± 1
L1536	1986[b]	4.9 ± 0.4
	1995 Jan	1.8 ± 1
V1057 Cyg.....	1986[b]	14.6 ± 0.7
	1996 June	18.3 ± 1
Elia 1–12	1986[b]	17.3 ± 0.9
	1996 June	15.25 ± 1

[a] W_{CO}: Equivalent width measured from 2.293 to 2.305 μm.

[b] Carr 1989.

4.3. *Upper Limits*

Table 4 presents upper limits for a subset of the sources where Carr (1989) did not detect CO features. In all of these sources we, too, failed to detect these features. To be consistent with Carr's methods, we calculated 3 σ upper limits determined from the noise in the continuum over the wavelength range 2.293–2.317 μm. Our upper limits are even lower than the ones presented by Carr, a fact that reflects both the lack of variability in these objects and our

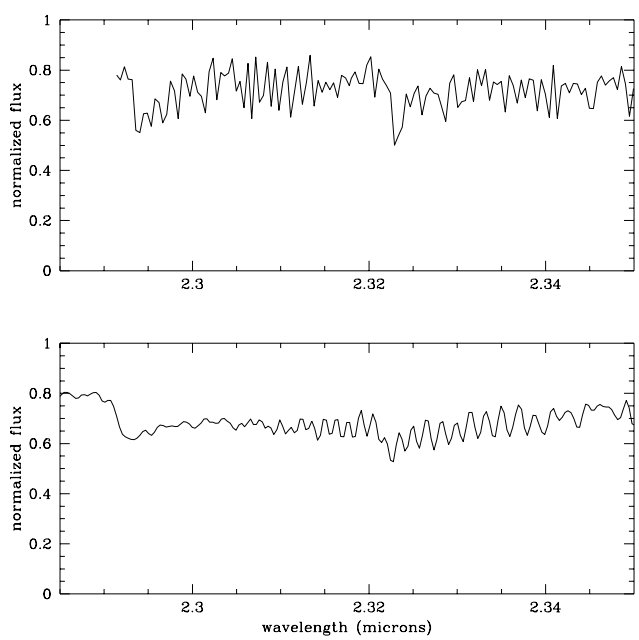

Fig. 5.—V1057 Cyg. *Top panel:* 1986 FTS spectrum (Hartmann & Kenyon 1987). *Bottom panel:* 1996 June spectrum. The transitions within the CO (2–0) and (3–1) bands are visible in both spectra. The equivalent widths of the individual lines have decreased.

TABLE 4

CO UPPER LIMITS

Object	UT Date	W_{CO}[a] (Å)
LkHα 198	1986[b]	1.8
	1995 Jan	0.44
CW Tau	1986[b]	1.6
	1995 Jan	0.25
Haro 6-10.....	1986[b]	4.2
	1995 Jan	0.69
SU Aur	1986[b]	1.9
	1995 Jan	0.52
PV Cep	1986[b]	3.3
	1996 June	0.55
LkHα 234.....	1986[b]	2.7
	1996 June	0.57
V645 Cyg	1986[b]	1.3
	1996 Sep	0.79

[a] W_{CO}: Equivalent width measured from 2.293 to 2.305 μm.

[b] Carr 1989.

improved spectral resolution and S/N. We note, however, that Geballe & Persson (1987) had observed emission in V645 Cyg.

5. CONCLUSIONS

We observed infrared CO first-overtone bands in a subset of the young stellar objects studied by Carr (1989). We find that the majority of objects with CO bands in emission are variable. The timescales for these variations can be as short as a few days, and in some cases the variations are recurrent events. There may be a periodic component of variability in DG Tau. Most objects with CO absorption have not been observed to vary, but V1057 Cyg is a noteworthy exception.

A variety of models have been proposed to explain the origin of CO first-overtone emission in YSOs. These include circumstellar disks, stellar or disk winds, magnetic accretion mechanisms such as funnel flows, and inner disk instabilities similar to FU Ori events. Variations in CO are generally expected with any of these models. However, the patterns of expected changes should differ. For example, funnel flows naturally account for periodic changes (although they could arise in other cases), while correlations with UV excess might result from variations owing to changes in accretion rate.

Future systematic monitoring of these variations is likely to provide important insights into the behavior of this class of objects and its relation to their evolutionary status.

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