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HIGH-RESOLUTION INFRARED SPECTRA OF FU ORIONIS VARIABLES: KEPLERIAN ROTATION AND MASS LOSS

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ABSTRACT

High spectral resolution 2 μm spectroscopy of two FU Orionis variables, V1057 Cyg and FU Ori, confirms our previous results that the ratio of infrared-to-optical $v \sin i$ in these objects is significantly smaller than unity. The observed ratio is slightly larger than predictions of simple accretion disk models but is consistent with strict Keplerian rotation given the uncertainties in the models.

Blueshifted CO v'–v'' = 2–0 absorption is observed in FU Ori and in V1057 Cyg, suggesting mass loss at rates less than $\sim 10^{-7}$ $M_{\odot}$ yr^{-1} from the outer disk regions. Our data suggest mass ejection in FU Ori is dominated by flows from inner disk regions. The mass-loss rate in FU Ori appears to be variable.

The heavily reddened FU Ori system V1735 Cyg has detectable, marginally resolved CO absorption features indicating a rotational velocity of $v \sin i \sim 20$ km s^{-1}. This result suggests a minimum mass for the central object of ~ 0.25 $M_{\odot}$.

Subject headings: infrared: spectra — stars: accretion — stars: individual (FU Ori, V1057 Cyg, V1735 Cyg) — stars: mass loss — stars: pre–main-sequence

I. INTRODUCTION

In several previous papers (Hartmann and Kenyon 1985, 1987*a*, *b*; Kenyon, Hartmann, and Hewett 1988; hereafter Papers I–IV), we have shown that accretion from a massive protostellar disk explains many observed properties of the FU Orionis objects. One important prediction of a Keplerian disk model is that the infrared spectrum, which is dominated by light from the outer disk, should exhibit smaller rotational line broadening than observed in optical spectral lines formed in inner disk regions. We observed this differential rotation from measurements at $\sim$6000 Å and at $\sim$2 μm in both FU Ori and V1057 Cyg (Papers II, III).

The velocity broadening of the CO 2 μm absorption lines in V1057 Cyg was only marginally resolved in our original data, and it seemed worthwhile to repeat the infrared measurements with higher spectral resolution. In this paper we report additional observations which confirm the differential rotation effect in V1057 Cyg and in FU Ori. From this third epoch of infrared observations we find no evidence for radial velocity variations in excess of 1–2 km s^{-1}, consistent with our single-star models but inconsistent with possible close binary models. We find new evidence for outflow in the v'–v'' = 2–0 CO absorption lines in V1057 Cyg, similar to previous results for FU Ori. We use these observations to suggest that the mass loss from FU Ori accretion disks varies strongly with radius, with the largest outflow from the innermost disk regions. We also report CO spectra of the heavily reddened FU Ori system V1735 Cyg (Elias 1978). The CO lines are marginally resolved on our spectra, with $v \sin i \sim 20$ km s^{-1}, requiring a minimum mass for the central object of ~ 0.25 $M_{\odot}$.

II. OBSERVATIONS AND RESULTS

High-resolution infrared spectroscopic observations were made on 1987 December 5–7 through a narrow-band CO filter with the 1.4 m Fourier transform spectrometer (FTS) at the coudé focus of the Mayall 4 m telescope. The data cover the spectral region 4150–4450 cm^{-1} (2.41–2.25 μm) at unapodized resolutions of 0.30 cm^{-1} (V1735 Cyg), 0.15 cm^{-1} (FU Ori), and 0.07 cm^{-1} (V1057 Cyg). Corrections for atmospheric absorption were made by ratioing object data with spectra of nearby A or B stars having comparable air masses. The spectra have not been flux-calibrated, because the observations were made in poor seeing.

Portions of our infrared spectra for V1735 Cyg and the M6 giant HR 4267 are presented in Figure 1. Although the V1735 Cyg spectrum has a signal-to-noise ratio (S/N) $\sim$ 7, CO v'–v'' = 2–0 and v'–v'' = 3–1 band heads are visible at 4305 cm^{-1} and 4360 cm^{-1}, respectively. This result confirms the original detection of CO absorption in this object by Elias (1978). FTS observations of V1057 Cyg and FU Ori have been described by Mould *et al.* (1978) and by us (Papers II–III). New spectra are presented in Figure 2. The new data are noiser than those discussed in earlier papers, but the general appearance of the spectra has not changed.

As in our previous papers on IR spectra of FU Ori objects, we performed a cross-correlation analysis to measure the radial velocities and line broadening of each object. This procedure takes advantage of the many absorption lines present in the spectrum and simplifies the extraction of information from regions of extensive line blending due to rapid rotation and the complexity of the spectrum. Details of our methods are discussed in Papers I–III. The radial velocity of an object relative to the template star is determined by the position of the correlation peak, while the line broadening can be measured by the width of the correlation peak.

Cross-correlations of V1735 Cyg and the M0 giant 2905 using HR 4267 as a template are shown in Figure 3. The correlation peak for V1735 Cyg is somewhat broader than that of the red giant comparison star, suggesting that the absorption lines are marginally resolved on our spectra. The observed width implies $v \sin i \sim 20$ km s^{-1}, which is similar to the width we reported for our initial observation of V1057 Cyg (Paper III).

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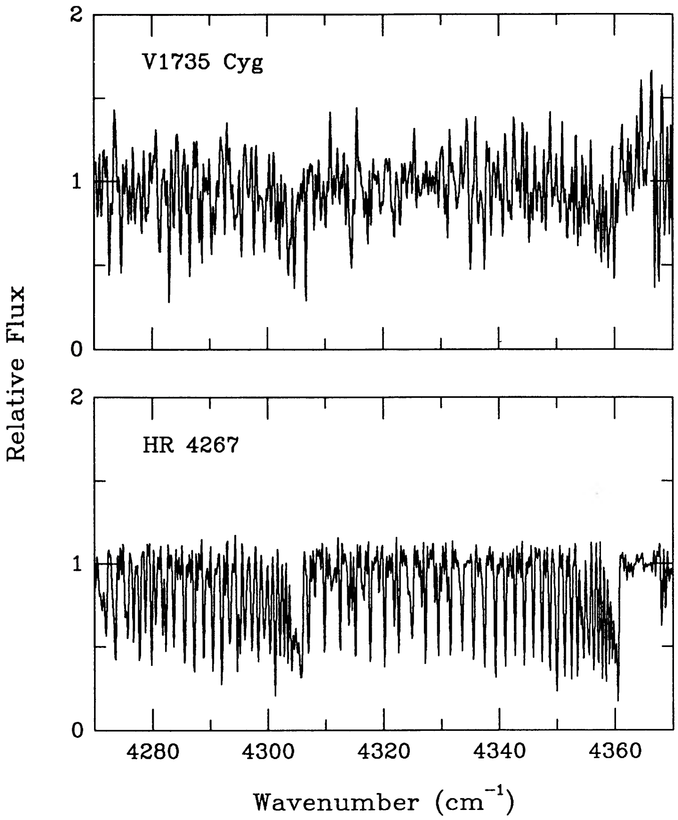

The heliocentric radial velocity derived from this spectrum is -10 km s^{-1} with an estimated error of ± 2–3 km s^{-1}, consistent with the velocity of -9 km s^{-1} obtained from radio CO observations of three positions in the associated IC 5146 star-forming region (Milman *et al.* 1975).

Cross-correlations of V1057 Cyg and FU Ori are presented in Figure 4. CO absorption lines were marginally resolved on our initial FTS spectra of V1057 Cyg (Paper III), and the higher resolution spectra described here allow us to see structure in the CO absorption lines for the first time. The $v'-v'' = 2$–0 correlation peak in V1057 Cyg (upper left panel of Fig. 4) is asymmetric and resembles the peak derived from our first infrared spectrum of FU Ori (see Paper II). The estimated heliocentric radial velocity of -21 ± 3 km s^{-1} is slightly blueshifted relative to our earlier infrared measurement of -15.7 ± 0.7 km s^{-1} in Paper III, the optical radial velocity (-14 to -16 km s^{-1}; Herbig 1977; Paper II), and the velocity of nearby interstellar gas (-12 to -16 km s^{-1}; Herbig 1977 and references therein).

The correlation peak for CO $v'-v'' = 3$–1 transitions in V1057 Cyg (lower left panel of Fig. 4) is symmetric and indicates a radial velocity of -13 ± 3 km s^{-1}. The peak appears to be doubled, but this result is of marginal significance due to the low signal-to-noise value of the cross-correlation peak

FIG. 1.—High-resolution infrared spectra of V1735 Cyg and HR 4267 (M6 III). CO band heads are visible at 4305 cm^{-1} ($v'-v'' = 3$–1) and 4360 cm^{-1} ($v'-v'' = 2$–0). The spectra have been divided by a spectrum of a nearby A star to remove telluric absorption lines.

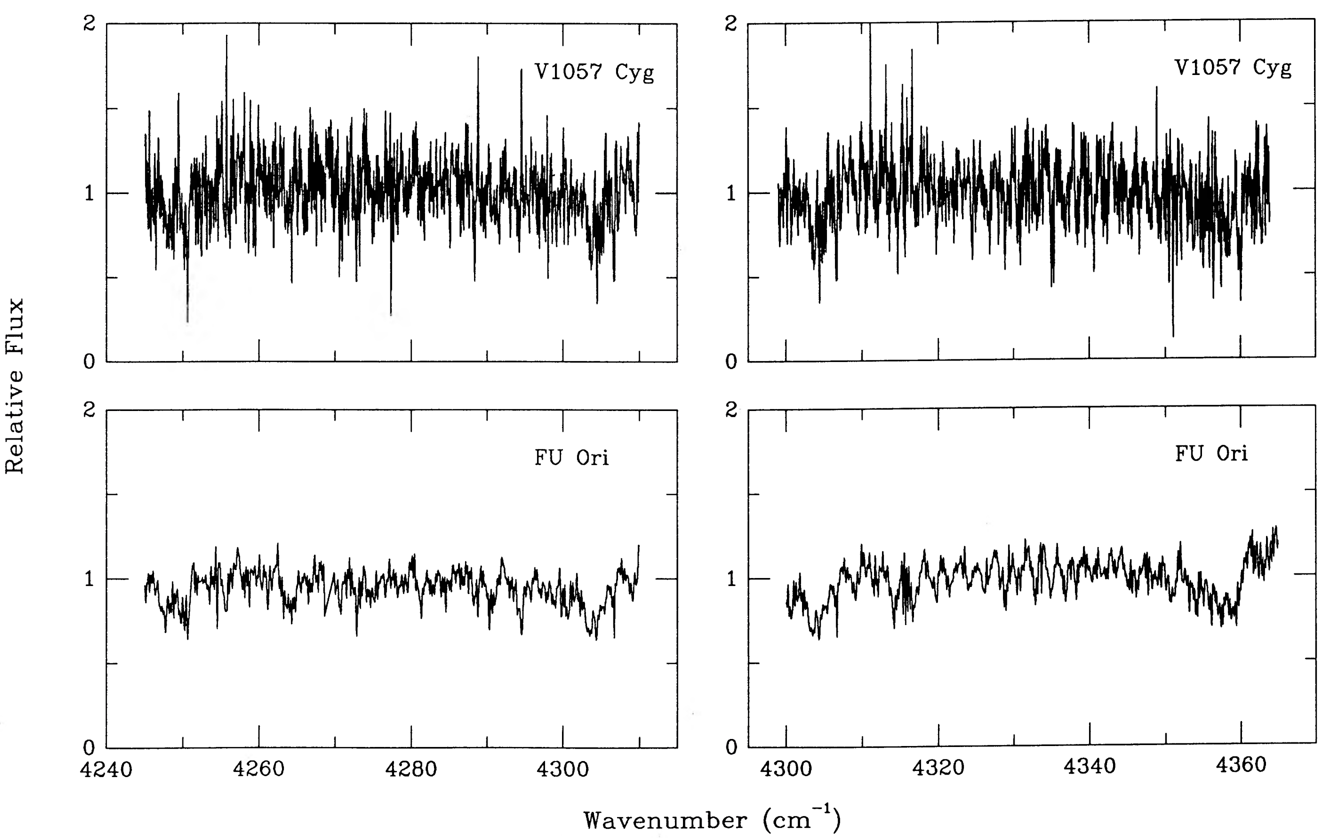

FIG. 2.—High-resolution infrared spectra of V1057 Cyg and FU Ori. CO band heads are visible at 4250 cm^{-1} ($v'-v'' = 4$–2), 4305 cm^{-1} ($v'-v'' = 3$–1), and at 4360 cm^{-1} ($v'-v'' = 2$–0).

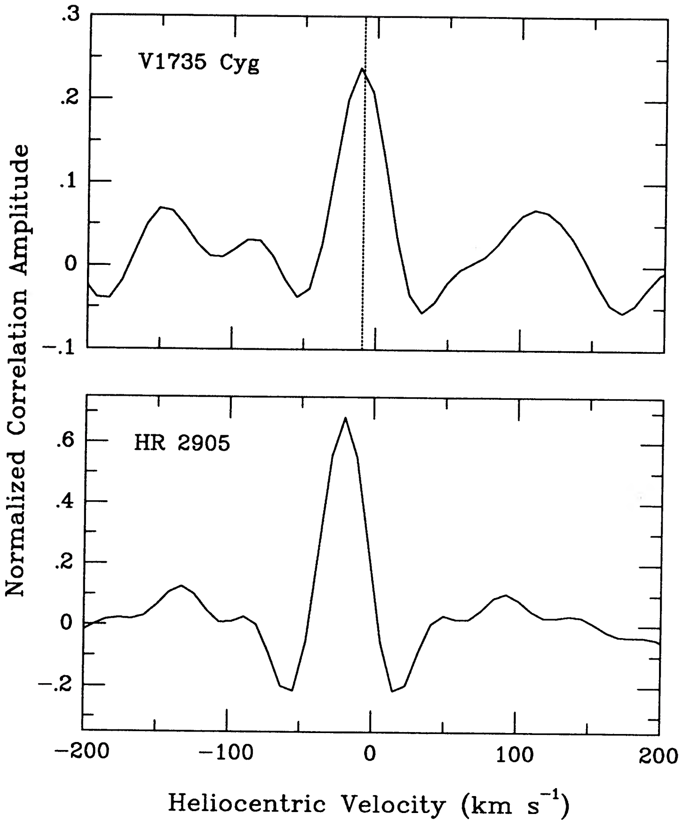

FIG. 3.—Cross-correlations of V1735 Cyg and HR 2905 (M0 III) against the spectrum of HR 4267. The CO lines of HR 2905 are unresolved on our spectra, and the correlation for V1735 Cyg is marginally broader than that of the M giant. Both cross-correlations are on a heliocentric velocity scale, and the velocity of interstellar material associated with V1735 Cyg is indicated by a dotted line.

($R = 4.3$; R is the ratio of correlation peak height to the rms noise; Tonry and Davis 1979).

There may have been some variability in the CO absorption profiles in FU Ori. The correlation peak derived for CO v'–v'' = 2–0 transitions (4300–4365 cm^{-1} region; upper right panel of Fig. 4) is slightly more symmetric and doubled than we reported in Paper II (see Fig. 5). The centroid of the correlation peak, as defined by the average velocity of the two zero crossings, is $+24 \pm 2$ km s^{-1}, marginally blueshifted from the systemic velocity of $+28$ km s^{-1} (Herbig 1977 and references therein), but slightly redshifted from the measurement of 20.5 ± 1.7 km s^{-1} in Paper II.

The correlation peak for v'–v'' = 3–1 transitions in FU Ori (4250–4315 cm^{-1} region; lower right panel in Fig. 4) also is more doubled than that of our first FTS spectrum (Fig. 5), but the radial velocity of $+26 \pm 2$ km s^{-1} measured from the present data is identical to the $+27.3 \pm 0.8$ km s^{-1} quoted in Paper II and the 28.2 ± 2.5 km s^{-1} inferred by Mould *et al.* (1978). Some of the zero-velocity correlation peak in FU Ori results from an incomplete cancellation of telluric absorption in the divided spectrum; however, the height of the telluric peak is small compared to the combined peak. The telluric absorption may be sufficient to produce the asymmetry in the

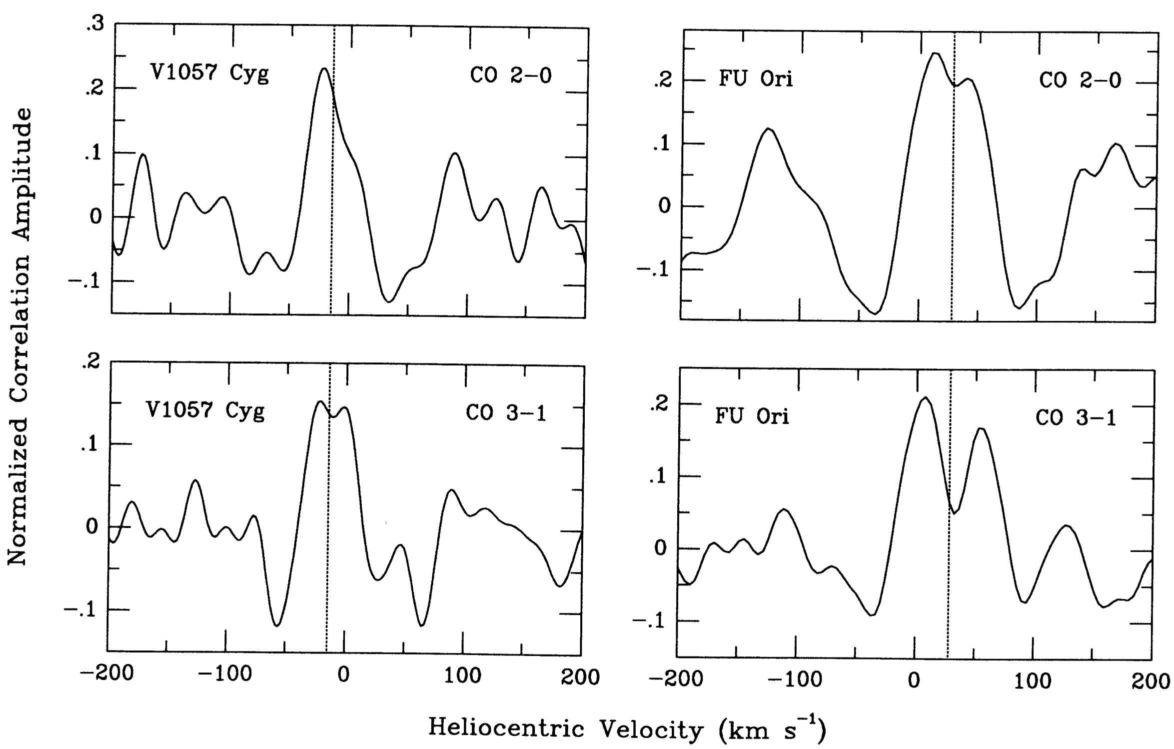

FIG. 4.—Cross-correlations of V1057 Cyg and FU Ori against the spectrum of M6 giant stars. *Top panels:* correlations of 4300–4365 cm^{-1} region containing CO v'–v'' = 2–0 absorption lines. The correlation of V1057 Cyg is asymmetric, which we interpret as a signature of mass loss. *Bottom panels:* correlations of the 4250–4315 cm^{-1} region containing CO v'–v'' = 3–1 absorption lines. Both correlations are doubled, as predicted by the disk model. The cross-correlations are on a heliocentric velocity scale, and the velocity of nearby interstellar material is indicated by a dotted line in each panel.

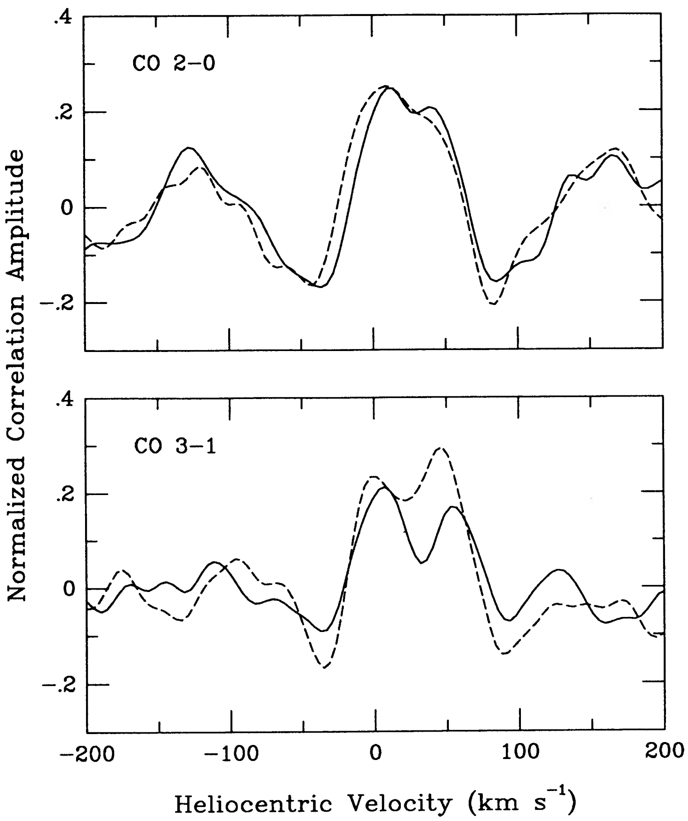

FIG. 5.—Comparison of FU Ori correlations obtained from 1986 data (*dashed lines*) and 1988 data (*solid lines*) for the two spectral regions shown in Fig. 2. CO absorption lines at 4300–4365 cm^{-1} (CO v'–v'' = 2–0 transitions) are more symmetric, more doubled, and less blueshifted in 1988 as compared with the 1986 results. Lines at 4250–4315 cm^{-1} (CO v'–v'' = 3–1 transitions) are essentially unchanged from 1986 to 1988; the variations in the correlation peaks are probably due to differences in the signal-to-noise ratio and the amount of residual telluric absorption in each spectrum.

two peaks shown in the lower right panel of Figure 4, but the asymmetry also could be the result of the relatively low signal-to-noise of the FTS spectrum.

III. COMPARISON OF DISK MODEL PREDICTIONS WITH OBSERVATIONS

a) V1057 Cygni and FU Orionis

An essential requirement of the Keplerian accretion disk model for FU Ori objects is that the $v \sin i$ derived from the width of IR correlation peaks should be measurably *smaller* than the optical $v \sin i$, and Paper IV showed that available observations of V1057 Cyg and FU Ori were in reasonable agreement with theory. Our higher resolution results for V1057 Cyg confirm our earlier finding. Although there is some variability in the IR correlations measured for FU Ori, the overall velocity widths of the profiles are not much different from those described previously. Thus, the conclusion that the IR line profiles are significantly narrower than the optical line profiles remains unchanged.

The results of the cross-correlation analysis indicate that the v'–v'' = 3–1 CO lines in FU Ori have doubled line profiles centered at the systemic velocity, an effect which also is in qualitative agreement with the predictions of the accretion disk model.

To compare the observations with disk model predictions in more detail, we have synthesized disk spectra as described in Paper IV. The disk is divided into many concentric annuli, each of which is assumed to radiate as a stellar atmosphere with a temperature, T_d. The radial temperature distribution of the steady disk is determined by a fit to the dereddened energy distribution in each object, and the results of this exercise are listed in Tables 3 and 4 of Paper IV. High-resolution spectra of K and M giants are used to represent the emitted infrared spectrum of each annulus; data for a given annulus are convolved with the line profile of a ring rotating at the appropriate Keplerian velocity and weighted according to the fractional contribution of the annulus to the total flux at the wavelength of observation. The sum of the weighted spectra is then cross-correlated against the template used for the actual observations. The normalization of the velocity scale is set by matching observed and synthetic optical cross-correlation peak widths. A direct comparison of synthesized and observed spectra is made difficult by the low signal-to-noise of the FTS data and the blending of broad CO absorption lines, so the synthesized correlation peaks serve to test the disk model predictions.

Observed and synthesized correlation peaks for V1057 Cyg are compared in the left panels of Figure 6. The optical (6170 Å) results are repeated from Paper IV; a new disk model was calculated for the higher resolution infrared data presented here, and its correlation is shown with the observed correlation in the lower left panel of Figure 6. The observed infrared correlation peak is slightly wider than the disk model peak. The amount of doubling and the width of the model line profile could be increased if outer, more slowly rotating regions of the disk do not contribute as much CO absorption to the spectrum as do inner, more rapidly rotating disk regions. We found in Paper IV that the observed correlation peak width in FU Ori could be reproduced if the CO absorption in disk material cooler than ~2000 K were masked by strong H_2O blanketing, an effect which is not included in our spectrum synthesis but is indicated by Carbon's (1987) preliminary model atmosphere calculations. A similar reduction of the model infrared rotational velocity would also improve the fit for V1057 Cyg.

The width of model line profiles can also be increased if the rotational velocity in the disk decreases more slowly than the Keplerian law, $v_\phi \propto r^{-1/2}$, *or* if the disk temperature decreases more rapidly than the steady-state law, $T_d \propto r^{-3/4}$. The success of steady-disk models in producing the observed energy distributions of FU Ori and V1057 Cyg argues against a modification of the radial temperature distribution used to construct the model line profiles, but our data do not preclude slight departures from Keplerian rotation (~20%, as judged from Fig. 6). More detailed model atmosphere calculations are required to quantify the significance of such deviations.

Our results for FU Ori are presented in the right panels of Figure 6. The observed optical correlation and both model correlations are repeated from Paper IV, while new data were employed to compute the observed CO v'–v'' = 2–0 correlation. Although we found that the observed CO lines were broader than predicted by the disk model in Paper IV, the agreement between the disk model and the new data for the CO v'–v'' = 2–0 region is excellent. We still find that the predicted correlation peak for CO v'–v'' = 3–1 transitions is narrower than the observed peak; as with V1057 Cyg, a better fit to the data can be achieved if cool disk material with $T_d \lesssim 2000$ K does not contribute to the CO absorption spectrum.

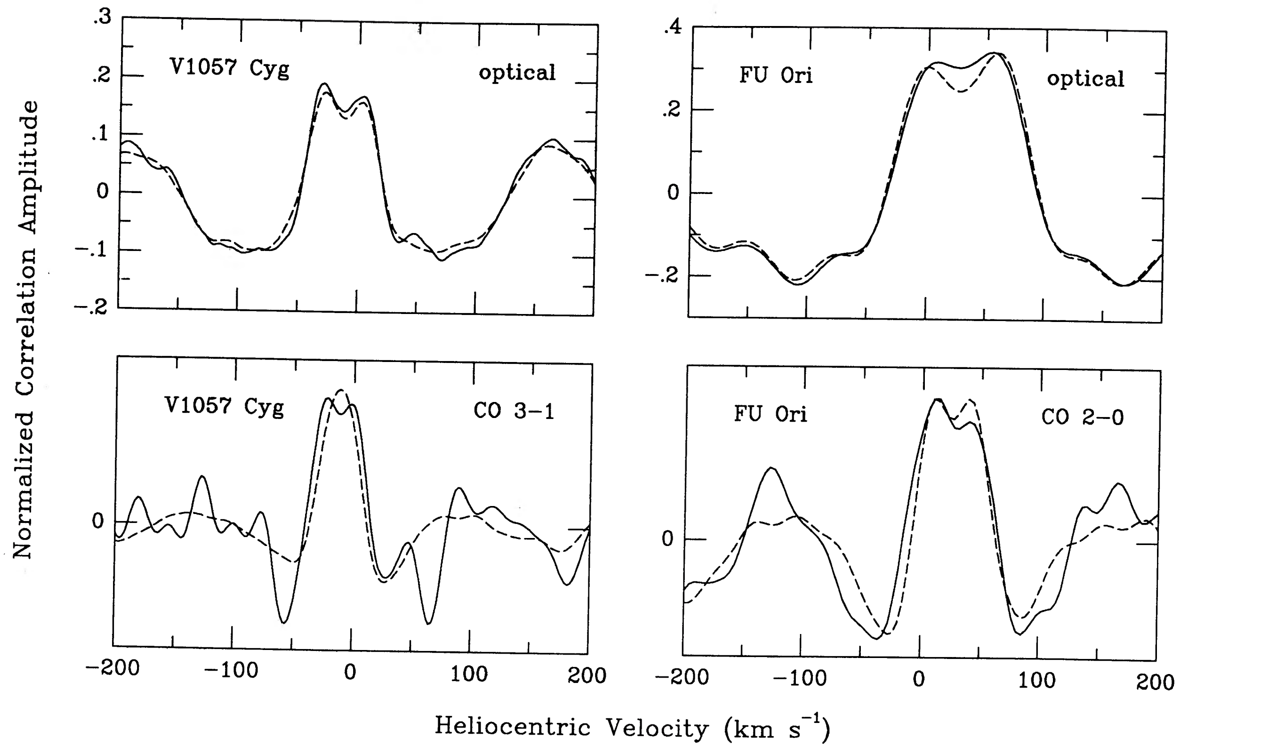

FIG. 6.—Comparison of observed (*solid lines*) and synthetic (*dashed lines*) correlation peaks for V1057 Cyg and FU Ori. The velocity scales of the optical models have been adjusted to obtain the correct correlation peak width.

In summary, the new observations of V1057 Cyg and FU Ori are consistent with the presence of a luminous accretion disk *in Keplerian rotation* about a central pre–main-sequence star. However, the physical cause for the rapid mass flow through the disk remains obscure. Gravitational instabilities (see, e.g., Hanami 1988) are a promising trigger for the eruption, because disk masses ~ 0.01–$0.1\ M_\odot$ are required to power the disk luminosity for the duration of a typical outburst (Papers I–IV; Hartmann *et al.* 1989). Our techniques are not sufficient to determine if the disk's self-gravity becomes important for disk radii exceeding $\sim 100\ R_\odot$, because the optical spectra probe disk material within 2–3 stellar radii (~ 10–$15\ R_\odot$) of the central star, while the infrared data test the model for regions at distances of 10–20 stellar radii (~ 50–$100\ R_\odot$).

b) V1735 Cygni

Elias (1978) discovered this FU Ori object during an IR survey of the IC 5146 dark cloud, and noted a 5 mag eruption in *R* between 1952 September and 1965 July. The system has remained at maximum for ~ 20 yr.

The large reddening, $A_V \sim 9$ mag (Elias 1978; Goodrich 1987), makes it difficult to determine an optical spectral type and the intrinsic energy distribution for this object, so it is not known if V1735 Cyg possesses the same spectroscopic peculiarities as do other FU Ori variables. Nevertheless, Elias's (1978) spectra and the data described in this paper demonstrate the presence of CO absorption lines with $v \sin i \sim 20$ km s^{-1}. Among pre–main-sequence stars, such features have been detected only in objects which have luminous accretion disks; the more normal T Tauri and Ae/Be stars appear to have CO *emission* or no CO features (Carr, Harvey, and Lester 1986; Hamann, Simon, and Ridgway 1988; Hartmann *et al.* 1989; Kenyon and Hartmann 1987).

The apparent detection of rotational broadening in V1735 Cyg constrains the mass of the infrared object. For an intrinsic infrared brightness of $K = 5.5$, the radius of a spherical object at a distance of 900 pc and having a blackbody temperature of 2000 K (Elias 1978) is $R_{\rm IR} \sim 120\ R_\odot$. Although the observed line width needs to be confirmed with higher resolution IR spectra, this large radius for V1735 Cyg requires the infrared object to rotate at the breakup velocity if it has a mass $M_{\rm IR} \sim 0.25\ M_\odot$ for $\sin i = 1$. The large reddening precludes an estimate of the optical $v \sin i$ in V1735 Cyg, but high-resolution observations at 1 μm should allow a search for the larger $v \sin i$ predicted by the disk model.

IV. MASS LOSS FROM FU ORIONIS ACCRETION DISKS

a) Empirical Estimates

The FU Ori objects show deep blueshifted absorption to velocities ~ 150–300 km s^{-1} in strong optical lines like Hα and Na I D (Bastian and Mundt 1985; Croswell, Hartmann, and Avrett 1987). This wind probably originates in the inner disk or boundary layer, because the optical lines are seen in absorption against a continuum produced in the inner disk regions. The high velocities also suggest ejection from deep in the gravitational potential well. Semiempirical wind models suggest a moderate temperature flow (~ 5000 K) where H is mostly neutral, and the observed Na I profiles suggest mass-loss rates $\sim 10^{-5}$ to $10^{-6}\ M_\odot$ yr^{-1} (Croswell, Hartmann, and Avrett 1987).

The ~ 10 km s^{-1} blueshifts seen in the CO v'–$v'' = 2$–0 absorption of FU Ori and V1057 Cyg also suggest mass ejection. We cannot be certain that mass loss is occurring, because the expansion is well below the expected escape velocity ~ 50–70 km s^{-1} (at the characteristic 2 μm disk radius, assuming a central mass of $\sim 0.5\ M_\odot$).

If mass loss is present, the CO absorption may originate in cold interstellar gas swept up by the fast wind detected in optical lines. We can estimate the column density in swept-up material under this hypothesis. From the results of Kirby-Docken and Liu (1978) and Chackerian and Tipping (1983), we estimate a mean oscillator strength for a given CO v'–v'' = 2–0 vibration-rotation transition of $\langle f \rangle \sim 4 \times 10^{-8}$. Then the average line optical depth is

$$\langle \tau_{2-0} \rangle \sim 1.5 \times 10^{-19} (\Delta v_{10})^{-1} N_{\rm CO} H \,, \qquad (1)$$

where Δv_{10} is the Doppler width in units of 10 km s^{-1}, and H is the length of the absorbing column.

We assume that all of the C is in CO, and that C has a number abundance of 5×10^{-8} relative to hydrogen. It seems likely that $\langle \tau_{2-0} \rangle \lesssim 1$ for CO gas at $V_{\rm exp} \sim$ 10–20 km s^{-1}. We see no direct evidence for any CO absorption features $\sim$50% deep in the spectra (Fig. 2), and the blueshifted component is a modest perturbation on the cross-correlation peaks (Figs. 4, 5). The implied column density for a broadening velocity of 3 km s^{-1} is 3×10^{21} hydrogen atoms cm^{-2}. This value for the swept-up shell is consistent with the observed reddening of $A_V \sim 2$ and normal dust-to-gas ratios (Savage and Mathis 1979).

While we note that the swept-up shell hypothesis is plausible, the data may indicate variability on a time scale $\sim$1 yr. The mass ejection of FU Ori and V1057 Cyg has continued for decades at speeds of hundreds of km s^{-1}, and by this time must have produced large expanding shells with time scales for evolution much longer than 1 yr. Further observations should be made to attempt to confirm variability, which would imply that the absorption arises close to the central object.

Another possibility is that the observed CO absorption is produced very close to the (infrared) disk photosphere in a low-velocity flow, and that the subsequent expansion of the wind renders the CO optically thin at higher velocities. Using equation (1) for the optical depth, the mass-loss rate from a flat disk is then

$$\dot{M} \sim 2 \times 2\pi R_{2\,\mu{\rm m}}^2 \rho v \sim 10^{-7} \langle \tau_{2-0} \rangle \Delta v_{10} \left(\frac{V_{\rm exp}}{10 \text{ km s}^{-1}} \right) \times \left(\frac{R_{2\,\mu{\rm m}}}{2.5 \times 10^{12} \text{ cm}} \right)^2 \left(\frac{H}{2.5 \times 10^{11} \text{ cm}} \right)^{-1} M_\odot \text{ yr}^{-1} \,. \qquad (2)$$

In the case of FU Ori, we take $R_{2\,\mu{\rm m}}$ to be the half-light disk radius at 2.2 μm and H to be the density scale height at this radius for $M = 0.5\ M_\odot$. Thus, $R_{2\,\mu{\rm m}} = 2.5 \times 10^{12}$ cm and $H = 0.1 R_{2\,\mu{\rm m}}$ (see Table 4 of Paper IV). The velocity shift $V_{\rm exp}$ is $\sim$10–20 km s^{-1}. We do not have a direct measurement of the Doppler width, but given the expansion velocity it is difficult for Δv_{10} to be much less than unity. We once again estimate that $\langle \tau_{2-0} \rangle = 1$. Then $\dot{M} \sim 10^{-7}\ M_\odot$ yr^{-1}.

We note that this mass-loss rate is an *upper limit* in the case where the material is not ejected to infinity, or if the absorption actually arises in a distant circumstellar shell. The only way to get a much higher ejection rate would be to suppose that most of the C is not in CO. However, this hypothesis seems quite unlikely, given the low temperatures required to avoid v'–v'' = 3–1 absorption, since

$$\frac{\langle \tau_{3-1} \rangle}{\langle \tau_{2-0} \rangle} = \frac{\langle f_{3-1} \rangle}{\langle f_{2-0} \rangle} \exp\left[-\frac{3080}{T} \right] \sim 2 \exp\left[-\frac{3080}{T} \right] .$$

Another alternative is to assume that broad CO absorption is present with a velocity width of $\sim$50 km s^{-1}, similar to the escape velocity, and is too broad to detect on our spectra. If we assume that the acceleration to an expansion velocity comparable to the escape velocity occurs over the characteristic disk radius, then $H \sim R_{2\,\mu{\rm m}}$. For $\langle \tau_{2-0} \rangle = 1$ and $V_{\rm exp} = 50$ km s^{-1}, the changes in $V_{\rm exp}$ and H are essentially complementary, so the resulting mass-loss rate is once again $\dot{M} \sim 10^{-7}\ M_\odot$ yr^{-1}.

The low, perhaps negligible, mass-ejection rate from the near-infrared emitting disk regions contrasts with optical studies which provide an order of magnitude estimate of $\dot{M} \sim 10^{-5}\ M_\odot$ yr^{-1} for FU Ori (Croswell, Hartmann, and Avrett 1987). While these estimates are uncertain, they do suggest the mass-loss rates decrease by a factor $\sim 10^2$ as R increases from ~ 1–$2 R_*$ to $\sim 10 R_*$. These calculations do not constrain any possible flows arising from larger disk regions.

The case for differing mass-loss rates between the optical and infrared regions is less clear in V1057 Cyg. The optical lines exhibit less blueshifted absorption than in FU Ori, suggesting a mass-loss rate of perhaps $\sim 10^{-6}\ M_\odot$ yr^{-1} (Croswell, Hartmann, and Avrett 1987). Considering the uncertainty in the estimates, the difference between this rate and the infrared upper limit of $\sim 10^{-7}\ M_\odot$ yr^{-1} has marginal significance.

Our recent observations of FU Ori may indicate less blueshifted CO absorption than before. In this regard we note that an optical spectrum taken one month following the infrared spectra also indicated substantially less blueshifted absorption in the Hα and Na I D lines (Fig. 7). At the same time, the photospheric line profiles did *not* change significantly, showing that the wind variability is not obviously reflected by the underlying disk. Croswell, Hartmann, and Avrett (1987) showed that changing the velocity gradient of an FU Ori wind model by an order of magnitude changes the mass-loss rate necessary for strong Na I absorption by a factor less than $\sim$3 (their Fig. 7). Thus the observed variability in the optical lines probably does not represent an order-of-magnitude change in the mass-loss rate. Because the optical wind profiles for FU Ori had remained relatively unchanged for some years (compare Bastian and Mundt 1985; Croswell, Hartmann, and Avrett 1987; see Fig. 7), continued monitoring would be useful to understand the nature of this change.

b) *Implication for Accretion Disk Wind Models*

Pudritz and Norman (1983, 1986) proposed that hydromagnetically accelerated mass loss from protostellar disks produces the angular momentum transfer necessary for disk accretion. In this model, the outflow is also collimated by the magnetic field, which forces material to remain in corotation with the disk out to large distances from the central object. For the wind to carry away the required angular momentum, the mass-loss rate in the wind, $\dot{M}_w$, at a characteristic disk radius, R_d, must be

$$\dot{M}_w = \left(\frac{R_{\rm A}}{R_d} \right)^{-2} \dot{M}_a \,,$$

where $\dot{M}_a$ is a mass accretion rate through the disk at R_d, and $R_{\rm A}$ is the Alfvén radius (measured *perpendicular* to the disk axis). FU Ori is well-fitted by steady accretion disk models with $\dot{M}_a \sim 10^{-4}\ M_\odot$ yr^{-1} (Paper IV). Thus, the inferred mass-loss rate of $10^{-5}\ M_\odot$ yr^{-1} from the inner disk requires only $R_{\rm A} \sim 3 R_d$, while the low upper limit to the CO mass-loss rate derived above for FU Ori requires an extremely large Alfvén

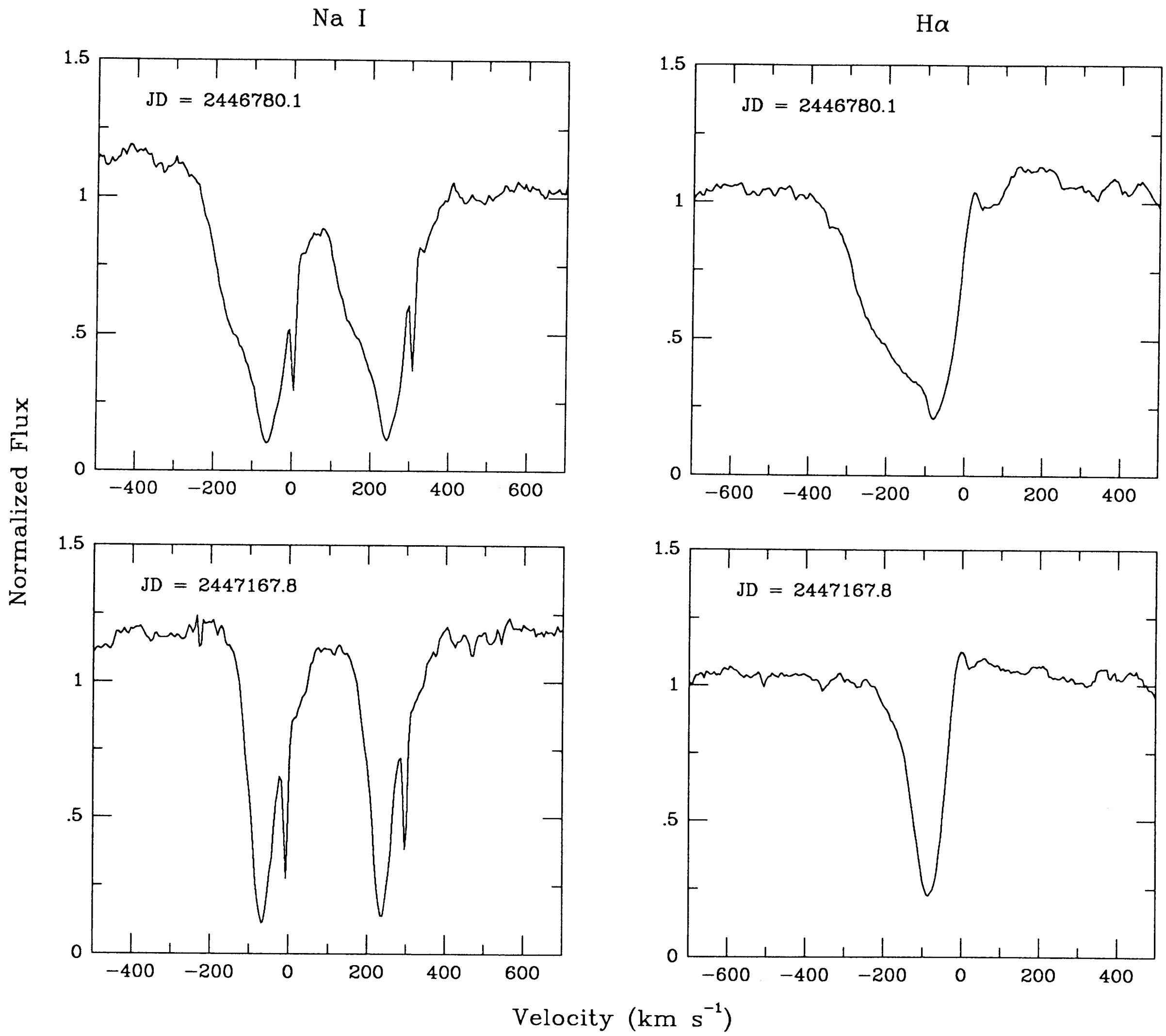

FIG. 7.—FU Ori profiles for Na I (*left panels*) and Hα (*right panels*). The wind components of both lines are much broader in 1986 September (*upper panels*) than in 1988 January (*lower panels*). The data were obtained with KPNO 4 m echelle by J. Stauffer.

radius of $R_A \gtrsim 30R_d$. Thus, the magnetic field must remain strong out to very large radii to carry away the required amount of angular momentum. Detailed calculations are required to verify if a plausible magnetic field strength at the disk surface can both carry away the required amount of angular momentum and collimate the wind to the degree observed; these calculations are beyond the scope of this paper.

The FU Ori results suggest that producing massive outflows from the outer regions of even a rapidly accreting disk is not a simple matter. The observations imply a two order of magnitude change in mass-loss rate over a change in radius of one order of magnitude or less. We find much greater mass loss from regions *deeper* in the gravitational potential well, a result suggested on theoretical grounds by Pringle (1988). The radial dependence of the magnetic field may play a crucial role in determining the mass-loss rate. Alternatively, turbulence generated in the inner disk accretion flow may help initiate mass ejection (Croswell, Hartmann, and Avrett 1987).

IV. SUMMARY

We have presented high-resolution 2 μm spectroscopy of three FU Orionis variables, V1057 Cyg, V1735 Cyg, and FU Ori. Our major conclusions can be summarized as follows.

1. The new spectra of V1057 Cyg clearly resolve the infrared rotation and confirm the $v \sin i$ measured in Paper III. The doubled line profile structure previously observed in FU Ori is marginally present in V1057 Cyg, and there is no evidence for radial velocity variations in either object. The ratio of infrared-to-optical $v \sin i$ in V1057 Cyg is identical to that found for FU Ori and is somewhat larger than the predictions of accretion

disk models. The larger infrared line widths may be caused by a lack of CO absorption in cool, slowly rotating disk regions.

2. The CO v'–v'' = 2–0 absorption lines are asymmetric in FU Ori and in V1057 Cyg, suggesting mass-loss rates less than $\sim 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$ from the outer disk regions. This mass-loss rate is considerably lower than the $\sim 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$ derived from optical spectra of FU Ori, suggesting that inner disk regions in this object are more effective in ejecting material.

3. V1735 Cyg has detectable, marginally resolved CO absorption features indicating a rotational velocity of $v \sin i \sim 20\ \mathrm{km\ s^{-1}}$, suggesting a minimum mass for the central object of $\sim 0.2\ M_\odot$.

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