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HIGH SPECTRAL RESOLUTION INFRARED OBSERVATIONS OF V1057 CYGNI

L. HARTMANN[1] AND S. J. KENYON[1]
Harvard-Smithsonian Center for Astrophysics
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ABSTRACT

We report high-resolution near-infrared spectra which confirm a key prediction of our accretion disk model for V1057 Cygni. In our model, the outbursts of V1057 Cyg and other FU Ori objects are caused by rapid accretion from a circumstellar disk nebula onto a pre–main-sequence star. Because slowly rotating outer regions of the disk model contribute most of the light at infrared wavelengths, while the more rapidly rotating inner disk regions dominate the optical spectrum, we predict that the observed rotational broadening of spectral lines should be smaller in the infrared than in the optical. High-resolution infrared spectra obtained with the KPNO 4 m FTS show that V1057 Cygni does rotate more slowly at 2.3 μm than at 6000 Å, by an amount quantitatively consistent with our simple disk models. Taken in conjunction with our earlier observations of FU Ori, which indicated a similar slowing of rotation from optical to infrared regions, our results strongly support the accretion disk model.

The absence of any radial velocity variations in either the infrared or optical spectral regions make it very unlikely that the accretion disk is fed by a companion star but support our proposal that the accreted material arises from a remnant disk of protostellar material.

Subject headings: stars: accretion — stars: individual (V1057 Cyg) — stars: mass loss — stars: pre–main-sequence

I. INTRODUCTION

It has been suggested that accretion of material from a circumstellar disk left over from the star-formation process may substantially alter the spectral appearance, activity, and evolution of young stars (Lynden-Bell and Pringle 1974; Mercer-Smith, Cameron, and Epstein 1984; Rucinski 1985; Adams, Lada, and Shu 1987). Accretion processes may also have important effects on the physical conditions in and evolution of proto–solar-system nebulae (e.g., Lin 1981; Mercer-Smith, Cameron, and Epstein 1984; Morfill and Volk 1984; Lin and Papaloizou 1985; Ruden and Lin 1986; and references therein). Because rates of mass and angular momentum transfer are highly dependent upon poorly understood turbulent viscosities, observations are required to demonstrate whether accretion at significant rates actually occurs.

In an earlier paper we suggested that the strongest observational case for disk accretion onto young stars at present comes from studies of the FU Orionis variables (Hartmann and Kenyon 1985, hereafter Paper I). We suggested that the energy for FU Ori outbursts is provided by accretion of 10^{-3} to 10^{-2} $M_\odot$ from a protostellar disk nebula over time scales of 10–100 yr. At these accretion rates, the disk and boundary-layer radiation dominates the stellar flux at all wavelengths.

One of the particular strengths of the disk model is the straightforward explanation of the observed variation of spectral type with wavelength. For example, FU Ori has an F type spectrum at 2800 Å (Ewald, Imhoff, and Giampapa 1986), an early-G supergiant spectrum in the optical (Herbig 1966, 1977), and an M type spectrum at 2 μm (Mould *et al.* 1978). The large radial gradient of surface temperature in an accretion disk naturally accounts for this effect, as the largest contributions to the spectrum at a particular wavelength come from regions with temperatures given by the Wien relation. Thus, the optical continuum emission comes from disk regions with temperatures ~ 5000 K at a characteristic radius $\sim 15\ R_\odot$, while the 2 μm spectrum arises from material with temperatures ~ 2000 K at radii $\sim 40\ R_\odot$.

The simple accretion disk model makes a fundamental prediction which can be tested observationally. If the optical spectrum arises from the hot inner disk regions, while the infrared emission comes from a much more extended region of the disk, Keplerian rotation must produce smaller rotational line broadening in infrared spectra than observed in the optical. In an earlier paper (Hartmann and Kenyon 1987, hereafter Paper II) we showed that this differential rotation between optical and infrared spectral regions is observed in FU Ori. Here we report similar measurements for V1057 Cyg, once again finding that the infrared rotation is measurably smaller than the optical $v \sin i$. This effect is directly contrary to models in which FU Ori objects are stars rotating near breakup (e.g., Mould *et al.* 1978), which predict that the infrared rotation should be larger than the optical values (since the infrared would arise from cool equatorial regions). The ratio of infrared to optical rotation in V1057 Cyg is in good quantitative agreement with predictions of the simple disk model.

Our observational results are described in § II. Quantitative comparisons between disk model predictions and our data are presented in § III, and we conclude with a brief summary of results in § IV.

II. OBSERVATIONS AND RESULTS

Infrared spectroscopic observations of V1057 Cyg and comparison stars were made on 1986 September 18, 19 with the 1.4 m Fourier transform spectrometer (FTS) at the coudé focus of the Mayall 4 m telescope. Three hour integrations on V1057 Cyg gave an rms signal-to-noise ratio of ~ 15 over the region 4000–5000 cm^{-1} (2.5–2.0 μm) at an unapodized resolution of

[1] Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatories, which is operated by AURA, Inc., under contract with the National Science Foundation.

0.15 cm^{-1} ($\sim$10 km s^{-1}). A mean extinction curve was derived for each night from three observations of the A2 Ia star α Cyg which bracketed two scans of V1057 Cyg. We have not flux-calibrated the data, because observations of photometric standard stars and V1057 Cyg were made through varying amounts of cirrus.

Portions of our infrared spectra of V1057 Cyg are presented in Figures 1 and 2, along with spectra of FU Ori and the M6 III giant HR 867 from Paper II for comparison. Strong ^{12}CO band heads are visible near 4305 cm^{-1} (v'–v'' = 3–1) and 4360 cm^{-1} (v'–v'' = 2–0), and a weak ^{13}CO band head may be present near 4264 cm^{-1} (v'–v'' = 2–0). The presence of strong ^{12}CO lines is inconsistent with the optical G supergiant spectrum, as noted by Mould *et al.* (1978), and are more comparable in strength to those observed in K–M giants and supergiants. A comparison of our spectra with the lower resolution data acquired by Mould *et al.* (1978) suggests that the CO features of V1057 Cyg have not changed much since 1977, despite the general photometric decline of the star (see Simon *et al.* 1981; Kopatskaya 1984).

The CO lines in V1057 Cyg appear broader than those visible in the M giant star but clearly are not as broad as those in FU Ori. We performed cross-correlation analysis to measure the line broadening in a way that takes advantage of the many lines in these spectra of modest signal-to-noise values. This procedure also simplifies the extraction of information from regions of extensive line blending due to rapid rotation and the complexity of the spectrum. Details of our procedure are given in Paper II. The position of the cross-correlation peak yields the radial velocity of the object relative to the template star, while the width of the cross-correlation peak is a measure of the line broadening in the object star. For objects with large rotational broadening, the cross-correlation peak has roughly the shape of the average line profile.

The cross-correlations of V1057 Cyg, FU Ori, and the M0 giant HR 2905 using HR 876 as a template star are shown in Figure 3. We focus on two spectral regions (4250–4310 cm^{-1} and 4300–4365 cm^{-1}), containing the v'–v'' = 3–1 and 2–0 band heads, respectively. The cross-correlation peaks for V1057 Cyg are clearly broader than those of the comparison M giant in both spectral regions. The observed width suggests $v \sin i \sim 20$ km s^{-1}, which would be an unusually large rotational velocity if V1057 Cyg were an M giant. The infrared cross-correlation peaks of V1057 Cyg are roughly half as wide as those observed in FU Ori. This result is not surprising, as

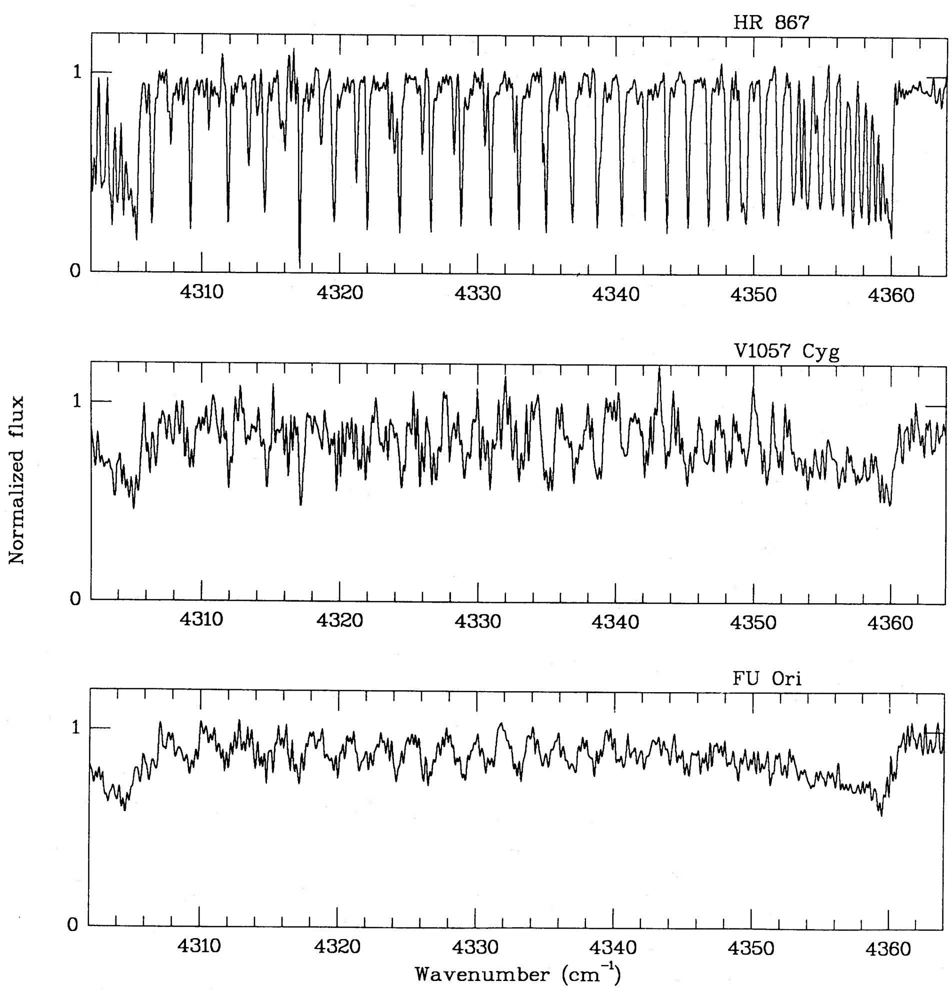

FIG. 1.—High-resolution IR spectra of HR 867 (M6 III), V1057 Cyg, and FU Ori, spanning the region of the ^{12}CO band heads at 4305 cm^{-1} (v'–v'' = 3–1) and 4360 cm^{-1} (v'–v'' = 2–0). The spectra have been divided by a spectrum of α Cyg corrected to the appropriate air mass to minimize absorption by telluric lines.

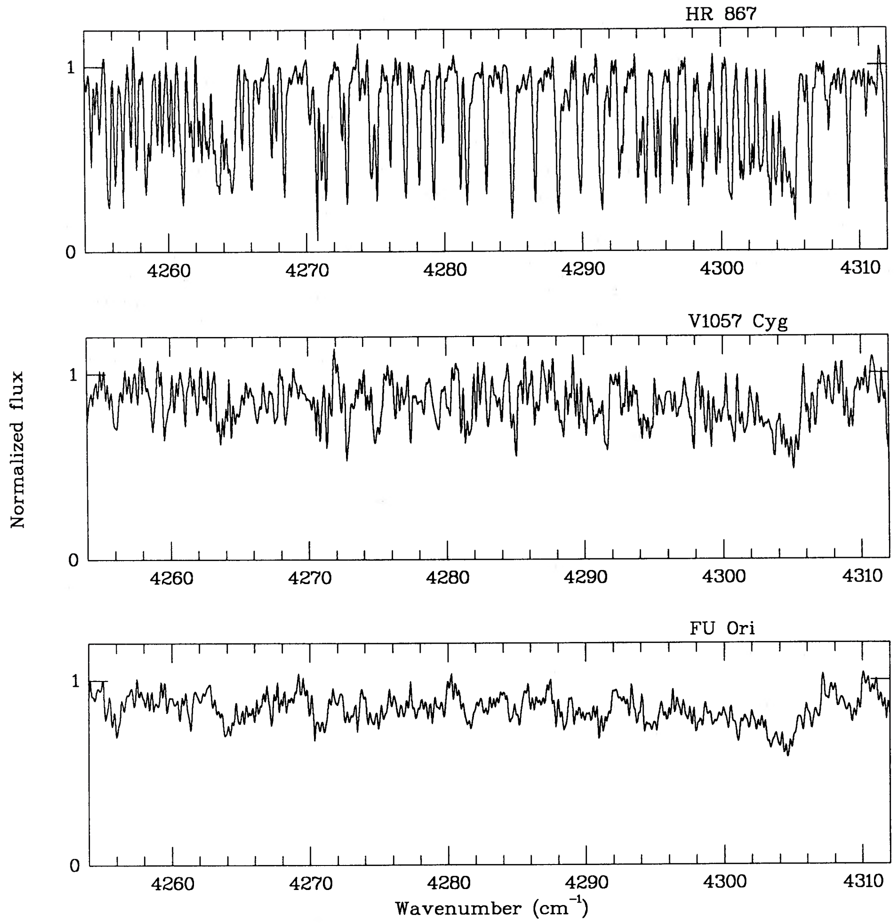

FIG. 2.—Same as Fig. 1 for a different wavenumber interval. The ^{13}CO v'–v'' = 2–0 band head is present at 4264 cm^{-1}, but is weak in the FU Ori objects relative to evolved M giants (see Mould *et al.* 1978).

the ratio of rotational velocities derived for these objects from optical spectra is also $\sim\frac{1}{2}$ (Papers I and II).

The heliocentric radial velocities measured from our spectra of V1057 Cyg are -15.7 ± 0.7 km s^{-1} (formal standard deviation from only two observations) in the 4300–4365 cm^{-1} region, and -15.6 ± 0.5 km s^{-1} in the 4250–4315 cm^{-1} region. These velocities are consistent with the -13.4 ± 3.5 km s^{-1} determined by Mould *et al.* (1978), the optical velocity of V1057 Cyg (~ -14 km s^{-1}, Herbig 1977; ~ -16 km s^{-1}, Paper II), and the velocity inferred from measurements of nearby interstellar material (~ -12 to -16 km s^{-1} as summarized by Herbig 1977).

In Paper II we attributed the double-peaked structure of the FU Ori cross-correlation in the 3–1 band head region to the rotational broadening of a flattened disk. As we show in the following section, our spectra do not have sufficient resolution to show such structure in V1057 Cyg even if it exists. We similarly see no evidence for an asymmetric correlation peak from analysis of the 2–0 region in V1057 Cyg, as is seen in FU Ori (Fig. 3). Again, insufficient resolution may prevent detection of any such asymmetry. If the asymmetry in the FU Ori cross-correlation peak arises from mass loss as suggested in Paper II, V1057 Cyg may not exhibit a similar effect because its mass-loss rate is lower (Croswell, Hartmann, and Avrett 1987).

III. DISCUSSION

a) Variation of Rotation with Wavelength: Comparison between Observation and Theory

In Figure 4 we compare the infrared cross-correlation peak of V1057 Cyg with the cross-correlation of the sum of many spectra taken at 6170 Å using the echelle spectrographs and intensified Reticon detectors on the Mount Hopkins 1.5 m and Multiple Mirror telescopes (Paper II). The resolution of the optical spectra is slightly better than the resolution of the FTS spectra. Although there is some ambiguity about the proper way to compare cross-correlation peaks, there can be no doubt that the rotational broadening of infrared lines in V1057 Cyg is less than the optical line broadening, confirming a key prediction of the accretion disk model.

We next develop a quantitative comparison between the observed and predicted dependence of rotation on wavelength. In Paper I we presented a steady accretion disk model which provided a good match to the energy distribution of V1057 Cyg. The model provides the relative surface brightness at wavelengths of interest as a function of radius. If the variation of equivalent width of the absorption lines as a function of temperature is known, the predicted spectrum can be synthesized and compared with observations.

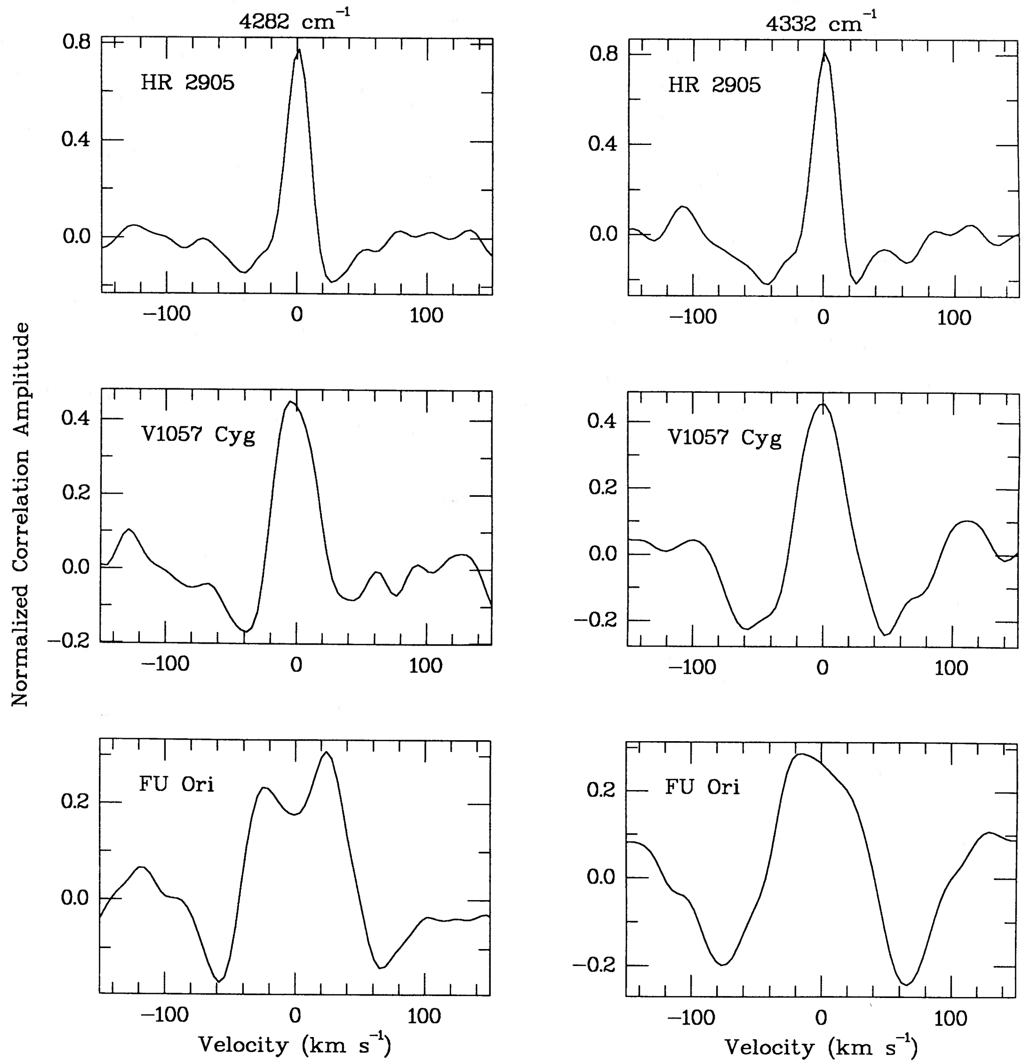

FIG. 3.—Cross-correlations of HR 2905, V1057 Cyg, and FU Ori spectra with the spectrum of HR 867 in both the 4250–4315 cm^{-1} and 4300–4365 cm^{-1} regions. The CO lines of HR 2905 are unresolved on our spectra, and CO lines of V1057 Cyg and FU Ori clearly are broader than those of a normal M giant. The peak of the cross-correlation for FU Ori in the 4250–4315 cm^{-1} region appears doubled, as predicted by the accretion disk model. The cross–correlation peak for FU Ori in the 4300–4365 cm^{-1} region is asymmetric, possibly due to mass-loss effects. All cross-correlations have been shifted to object rest-frame velocities. In the cases of V1057 Cyg and FU Ori, the heliocentric velocity shifts are consistent with previous measurements from optical spectra, and with the velocities of neighboring interstellar material.

We are presently engaged in an effort to perform such spectrum synthesis, using spectra of standard supergiant stars to represent the emergent fluxes from disk annuli of the same effective temperature (Kenyon, Hartmann, and Hewett 1988). For this paper we perform a simpler analysis, along the lines adopted in Paper II. We compute the profile of an "average" line, composed of contributions from different annuli with different Keplerian rotations and differing surface brightnesses. This mean line profile is then convolved with the instrumental broadening function twice and compared with the cross-correlation peak. (The instrumental profile enters twice in the cross-correlation since it is present in both the object and template star.) The profiles can be scaled in both strength and in width, since the mass and sin i of the object are not known. However, the ratio of the velocity widths of the resulting profiles is fixed by the requirement of Keplerian rotation and the surface temperature gradient of the disk model.

Observations indicate that the principal, saturated lines observed at 6170 Å do not vary much in equivalent width between effective temperatures of about 6600 K and 3300 K. Below this temperature region the typical lines become much weaker and TiO features become prominent. We therefore assume that the mean equivalent widths of lines in the 6170 Å optical echelle spectra are constant between 6600 K and 3300 K, and zero outside this temperature range.

Similarly, infrared observations indicate that the CO bands at 2 μm are very weak in supergiants and giants for effective temperatures greater than or $\sim$5000 K, and rapidly saturate to nearly constant equivalent widths at cooler temperatures. We extrapolate this constancy of CO line equivalent width down to 900 K. Although there are no stellar spectra with effective temperatures below 3000 K to compare with, this extrapolation may not be too bad because the CO lines are so highly saturated in atmospheres of the appropriate surface gravities (supergiants). At the very low temperatures characteristic of the outer disk regions in our model, dust might survive, and so

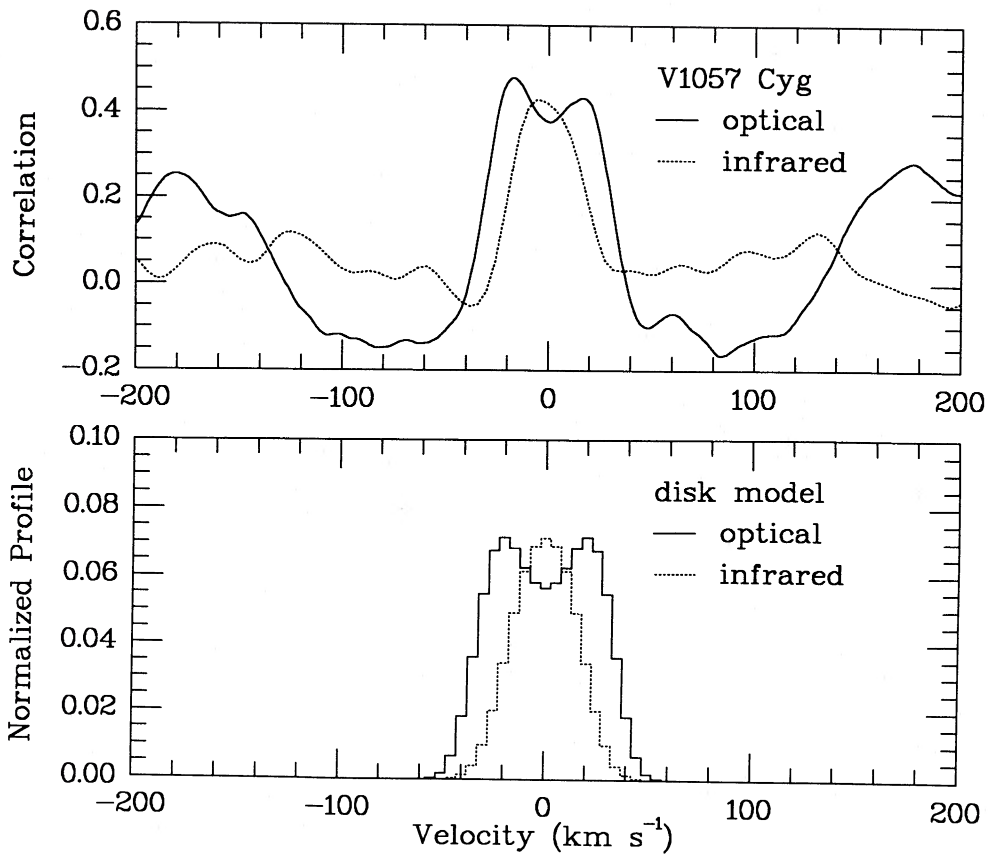

FIG. 4.—Comparison of observed (*upper panel*) infrared and optical correlation peaks for V1057 Cyg with the line profiles predicted by the accretion disk model (*bottom panel*). Only the ratio of velocity widths of the disk model profiles is meaningful; the widths have been scaled to achieve the best match with observation. The observed infrared rotational velocity is smaller than the optical rotation, as expected for a differentially rotating, luminous accretion disk.

carbon (and thus CO) may be depleted. We ignore this possible effect.

Figure 4 shows the results of these pseudo–line-profile calculations. The velocity scale has been established by scaling the optical profile to the observed optical cross-correlation peak; this procedure fixes the calculated infrared profile width. Although the exact correspondence between these calculations and cross-correlation peaks is somewhat uncertain, it is clear that the disk model does quite well in accounting for the observed wavelength dependence of rotation. The calculations also show that even if V1057 Cyg has double-peaked line profiles in the infrared, our spectral resolution was insufficient to detect such structure. The rotational velocities predicted by this simple model are within 10% of those determined by more detailed spectral synthesis (Kenyon, Hartmann, and Hewett 1988).

b) *Alternatives to the Disk Model*

We already noted that the slower infrared rotation in FU Ori and V1057 Cyg rules out models in which FU Ori objects are stars rotating near break-up velocities (Mould *et al.* 1978; Larson 1980). In such models, the infrared spectrum arises from an extended equatorial region which must be rotating more rapidly than the hot pole responsible for the optical spectrum, whereas we find the infrared lines exhibit less rotational broadening than in the optical.

Models in which the wavelength-variation of FU Ori spectra is explained by the presence of noninteracting G supergiants and M giants have never been very attractive, as they provide no explanation of outburst behavior. These models are now ruled out by the time decay of the near-infrared continuum in V1057 Cyg (see Simon *et al.* 1981; Kopatskaya 1984), which follows the optical decline and thus demonstrates a causal connection between the two spectral regions.

An alternative model explored in § III*a* of Paper I hypothesized mass transfer from a companion "M giant" filling its Roche lobe. While a lobe-filling giant might be rotating rapidly due to tidal synchronization in this scenario, its projected rotational velocity still must be smaller than the *difference* in the projected orbital velocities of the two binary components (since the orbital separation must be larger than the giant's radius). Although we have limited time coverage of V1057 Cyg and FU Ori in the infrared, the observations show no evidence for radial velocity variations exceeding 3 km s^{-1}, which is comparable to the upper limit on radial velocity variations in the optical region (Herbig 1977; Paper II). Since the observed $v \sin i$'s of FU Ori and V 1057 Cyg in the infrared are a factor of ~ 10 *larger* than the upper limit on radial velocity variations, we are confident that the rapid infrared rotation is not a result of synchronization in a close binary system.

Adams, Lada, and Shu (1987) have shown that the broadband energy distribution of FU Ori also can be fitted by a model in which a circumstellar disk reprocesses radiation from a central G type star. This model does not explain the outburst, the mechanism which produces a rapidly rotating G supergiant after outburst (apparently from a previously existing T Tauri star; Herbig 1977), or the observed variation of spectral type with wavelength in the optical region (Herbig 1977). The star-reprocessing disk model does not require any particular ratio of optical to infrared rotation in FU Ori objects, and so it does not explain why the optical and infrared rotations of FU Ori and V1057 Cyg seem to scale in roughly the same way. In addition, as pointed out in Paper II, the observed ratios of infrared to optical rotation suggest that the optical object is rotating roughly at break-up velocities. This result is quite strong if one assumes, as do Adams, Lada, and Shu (1987), that the infrared spectrum comes from a disk. In this case the infrared $v \sin i$ must represent the Keplerian velocity at a characteristic radius for the 2 μm emission. Since the Adams, Lada, and Shu model must have essentially the same ratio of characteristic radii at 6000 Å and at 2 μm as the accretion disk model to produce similar spectral energy distributions, it follows that the ALS model would require the optical object to rotate at essentially break-up velocity. If it must be assumed that the optical object is rotating at Keplerian velocity, one might as well assume that it is part of the accretion disk, which has the advantage of explaining the peculiar line profiles observed in optical spectra of V1057 Cyg (Papers I, II) as well as the optical outburst.

IV. SUMMARY

We have presented high-resolution infrared spectra of V1057 Cyg, which show that V1057 Cyg rotates more slowly in the infrared than in the optical. This differential rotation is predicted by our accretion disk model for FU Ori eruptions (Paper I) and has now been observed in the two brighest members of the class. The disk model also naturally accounts for a wide variety of phenomena observed in FU Ori objects, including double-peaked absorption line profiles, variation of spectral type with wavelength, important eruption time scales, and bipolar mass outflow (Papers I and II). We conclude that the case for luminous, differentially rotating disks in these systems is quite strong.

We have found no evidence for radial-velocity variability greater than ~ 3 km s^{-1} from optical or infrared spectra of any FU Ori object. Thus it seems unlikely that the accretion disk is fed by a companion star. It is more plausible that the accreted material comes from a disk remnant of the star-formation process.

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L. HARTMANN and S. J. KENYON: Center for Astrophysics, 60 Garden St., Cambridge, MA 02138