THE ASTROPHYSICAL JOURNAL, 312:243–253, 1987 January 1

FURTHER EVIDENCE FOR DISK ACCRETION IN FU ORIONIS OBJECTS[1]

L. HARTMANN[2] AND S. J. KENYON[2]
Harvard-Smithsonian Center for Astrophysics
Received 1986 April 9; accepted 1986 June 16

ABSTRACT

We report new observations supporting our hypothesis that rapid disk accretion onto pre–main-sequence stars causes the outbursts of FU Orionis objects. High-resolution infrared spectra show that FU Ori rotates rapidly in the 2 μm spectral region, ruling out models in which the infrared spectrum is produced by a normal M giant companion to the optical G-type component. The rotation measured from infrared CO lines is smaller than the rotational velocity measured in the optical region. This effect is predicted by the accretion disk model, in which the cooler, outer parts of the disk producing the infrared spectrum are rotating more slowly than the hot, inner disk regions responsible for the optical spectrum. The ratio of optical to infrared rotational velocities is in fair agreement with the prediction of our simple disk model.

Cross-correlation analysis of our infrared spectra indicates that the v'–v'' 3–1 CO lines in FU Ori have double-peaked profiles, another effect produced by a rotating flat disk. We also report optical spectra of V1057 Cyg providing additional evidence for double-peaked profiles in red photospheric lines.

Optical spectra of FU Ori, V1057 Cyg, and V1515 Cyg provide no evidence for radial-velocity variability $\gtrsim 3$ km s^{-1}. The infrared data for FU Ori similarly show no indication of velocity variations. These results make it very unlikely that the accretion disk is fed by a companion star but are consistent with our original proposal that the accreted material arises from a remnant disk of protostellar material.

Subject headings: stars: accretion — stars: individual — stars: pre–main-sequence

I. INTRODUCTION

We have recently proposed that the outbursts of FU Orionis objects are caused by the onset of disk accretion onto T Tauri stars (Hartmann and Kenyon 1985, hereafter Paper I). Observed outburst luminosities of several hundred $L_\odot$ over periods $\sim$10–10^2 yr require accretion of 10^{-3} to 10^{-2} $M_\odot$, a plausible amount of mass for a remnant circumstellar nebula. Crude estimates of thermal and viscous timescales for an accretion disk indicate that a disk instability mechanism can account for the rapid rise to optical maximum and slow decay of the light curve. A hot, optically thick accretion disk naturally accounts for the peculiar observed dependence of spectral type with wavelength, wherein the object has a G-type spectrum in the optical but an M-type spectrum at 2 μm (Herbig 1977; Mould *et al.* 1978). Simple disk models also reproduce the color evolution of V1057 Cyg during its decline from maximum light.

The disk model makes two clear predictions. If the luminous surfaces of FU Ori objects are rotating, flattened disks rather than spheres, the absorption-line profiles should be double-peaked. In Paper I we reported evidence for doubled line profiles from three MMT echelle spectra of V1057 Cyg. Herbig and Petrov (1986) had also reported evidence for such profiles in one spectrum of FU Ori. However, high signal-to-noise observations are required to observe double-peaked profiles in weak lines, as the profiles of strong lines are generally affected by mass ejection (Paper I; Herbig 1966, 1977). Recent spectra of FU Ori provide no additional evidence of doubled profiles (Herbig 1986). Additional observations are needed to confirm the reality of this line profile structure.

Another important prediction of the disk model is that the apparent rotational velocity should be wavelength-dependent. The optical region is dominated by light from the hot, inner portions of the disk, while the infrared spectrum is produced by the cooler, outer parts; this temperature variation accounts for the observed change in spectral type with wavelength. As the disk is presumed to be in Keplerian rotation around the central mass, the rotational velocity measured at infrared wavelengths should be smaller than the $v \sin i$ measured in the optical region.

In this paper, we present optical and infrared spectroscopy to test these predictions of the disk model. Observations with the Kitt Peak 4 m FTS and with the MMT and the 1.5 m telescopes on Mount Hopkins show that FU Ori rotates more slowly at 2 μm than it does at 6170 Å. Cross-correlation analyses of new optical spectra of V1057 Cyg provide further evidence for double-peaked absorption profiles.

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

II. OBSERVATIONS AND RESULTS

Infrared observations of FU Ori and comparison stars were obtained on 1986 January 29–30 with the 1.4 m Fourier Transform Spectrometer (FTS) at the coude focus of the Mayall 4 m telescope. A 4 hr integration on FU Ori gave an rms signal-to-noise ratio of $\sim$50 over the region 4000–5000 cm^{-1} (2.5–2.0 μm) at an unapodized resolution of 0.15 cm^{-1} ($\sim$10 km s^{-1}). A mean extinction curve was derived from observations of the B2 III star γ Ori at air masses of 1.1, 1.3, and 1.9. Since subsequent observations of photometric stan-

[1] Research reported herein used the Multiple Mirror Telescope, a joint facility of the Smithsonian Institution and the University of Arizona.

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

dard stars were made through varying amounts of cirrus, we have not flux calibrated the data.

Optical spectra of FU Ori, V1057 Cyg, and V1515 Cyg were obtained with the intensified reticon detectors on the echelle spectrographs of the MMT and the Whipple Observatory 1.5 m telescope. Further details of the instrumentation are given by Latham (1982). Spectra from two echelle orders were studied, centered at 5200 Å and at 6170 Å. Detailed properties of optical spectra of the three FU Ori objects are discussed in Paper I.

a) FU Orionis: Infrared Profiles

The infrared spectrum of FU Ori exhibits strong ^{12}CO bands which are inconsistent with the optical G supergiant spectrum, as noted by Mould *et al.* (1978). We further confirm the absence of Brγ (2.17 μm) found by these investigators at lower resolution. The FU Ori infrared spectra more closely resemble those of K and M giants, which do not display hydrogen absorption.

In Figure 1 we display a portion of the FTS infrared spectrum of FU Ori, along with the same region in the M6 III giant HR 867 for comparison. The FU Ori spectrum represents 2 hr of integration, or about half of the total exposure available. The CO v'–v'' 3–1 band head is apparent near 4304 cm^{-1}. In general, CO lines in FU Ori are very broad, undoubtedly due to the effect of rotation. This rules out models in which a G supergiant is paired with a normal, nonrotating M giant companion to produce the observed FU Ori spectra (Mould *et al.* 1978).

As described in Paper I, our basic analysis consists of cross-correlating spectra of the FU Ori objects with spectra of standard stars. Cross-correlation analysis enables us to use information from many spectral regions at once, improving the signal-to-noise of the result. This procedure also simplifies the extraction of information from regions of extensive line blending due to rapid rotation and the complexity of the spectrum. The position of the cross-correlation peak yields the radial velocity of the object relative to the template star. 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.

We chose wavelength intervals with 1024 data points for cross-correlation analysis and adopted cosine-bell endmasking over the initial and final 10% of the spectrum (Brault and White 1971). The analysis was limited to wavelength regions in which telluric lines were relatively infrequent. Experimentation with various K and M giants as template stars showed that the latest standard observed, HR 867 (M6 III), provided the highest signal-to-noise correlation peaks. This result is consistent with the very low temperature estimated for the infrared spectrum by Mould *et al.* (1978).

In Figure 1 we present the cross-correlation of FU Ori with HR 867 in the spectral region 4250–4310 cm^{-1}. The peak of the cross-correlation is very broad, with a FWHM $\approx$ 90 km s^{-1}. Cross-correlations of HR 867 with other M and K giants yield cross-correlation peak widths of only $\sim$20 km s^{-1}, using the same spectral region, resolution, and filtering in frequency. The cross-correlation peak for FU Ori also has two maxima. This appears to be a real effect; the cross-correlation for the other 2 hr exposure is similarly double-peaked. As noted in Paper I, double-peaked line profiles are not characteristic of rotating spheres but are predicted to occur for rotating rings or disks.

Incomplete cancellation of telluric lines might produce a spurious correlation peak near the position of the cross-correlation peak at +45 km s^{-1} heliocentric velocity. We tested our sensitivity to this effect in two ways. First, we cross-correlated our template spectrum against the uncorrected γ Ori spectrum; a very small cross-correlation peak resulted. We also formed the ratio of two γ Ori spectra taken at different air-mass values. This ratio indicated three spectral regions where telluric lines were strongly dependent upon air mass. We deleted these spectral regions from the FU Ori spectrum prior to cross-correlation. The resulting cross-correlation peak differed from that shown in Figure 1 (*third panel*) by an imperceptible amount. We conclude that incomplete telluric line cancellation is not an important factor determining the correlation peak shape shown in Figure 1.

In Figure 1 we also show for comparison the cross-correlation of the sum of all our echelle spectra of FU Ori in the 6170 Å region. A comparison of the optical and infrared correlation peaks shows that rotational broadening in the infrared is smaller than it is in the optical spectra. In § III we discuss the correlation widths in quantitative detail for comparison with disk model predictions.

The heliocentric radial velocity of +27.3 $\pm$ 0.8 km s^{-1} (formal standard deviation from only two observations) measured from these infrared spectra agrees quite well with the value of 28.2 $\pm$ 2.5 km s^{-1} derived by Mould *et al.* (1978) from a low-dispersion FTS spectrum of FU Ori in 1977. The infrared radial velocity also agrees quite well with the optical velocity and the velocities of associated interstellar material (Herbig 1977).

In Figure 2 we exhibit cross-correlations using the 4300–4365 cm^{-1} region. This spectral bandpass is dominated by the v'–v'' 2–0 overtone lines of CO; the band head is visible near 4360 cm^{-1}. In this case, the correlation peak is not doubled. The heliocentric radial velocity derived by fitting a parabola to the correlation peak is 20.5 $\pm$ 1.7 km s^{-1}, which is substantially blueshifted from the velocity derived from the 3–0 overtone as discussed above.

Optical spectra of FU Ori show that the strongest absorption lines exhibit blueshifted "shell" absorption components (Herbig 1977), which demonstrate the existence of dense, low-temperature outflow. These components can skew the correlation peaks to more negative velocities; the effect is more prominent in strong lines, while weak lines are much more symmetric (Paper I). In a low-temperature gas, absorption in the 2–0 lines is likely to be stronger than in the 3–1 transitions. We therefore interpret our results to indicate that mass ejection is being detected in the 2–0 CO transitions, which blueshifts the correlation peak. The good agreement of the 3–1 transition radial velocities with the optical and molecular velocities argues that these lines are not strongly affected by mass loss. Therefore we believe that the cross-correlation of the 3–1 overtone region is much more representative of the average infrared photospheric line profile than the correlation peak for the 2–0 overtone.

We also attempted to perform cross-correlations for the spectral region encompassing the 4–2 overtone bandhead. Incomplete cancellation of several very strong telluric features makes the results from this spectral region less secure than for the other two regions discussed above. We can say that the correlation peak width is comparable with the results discussed

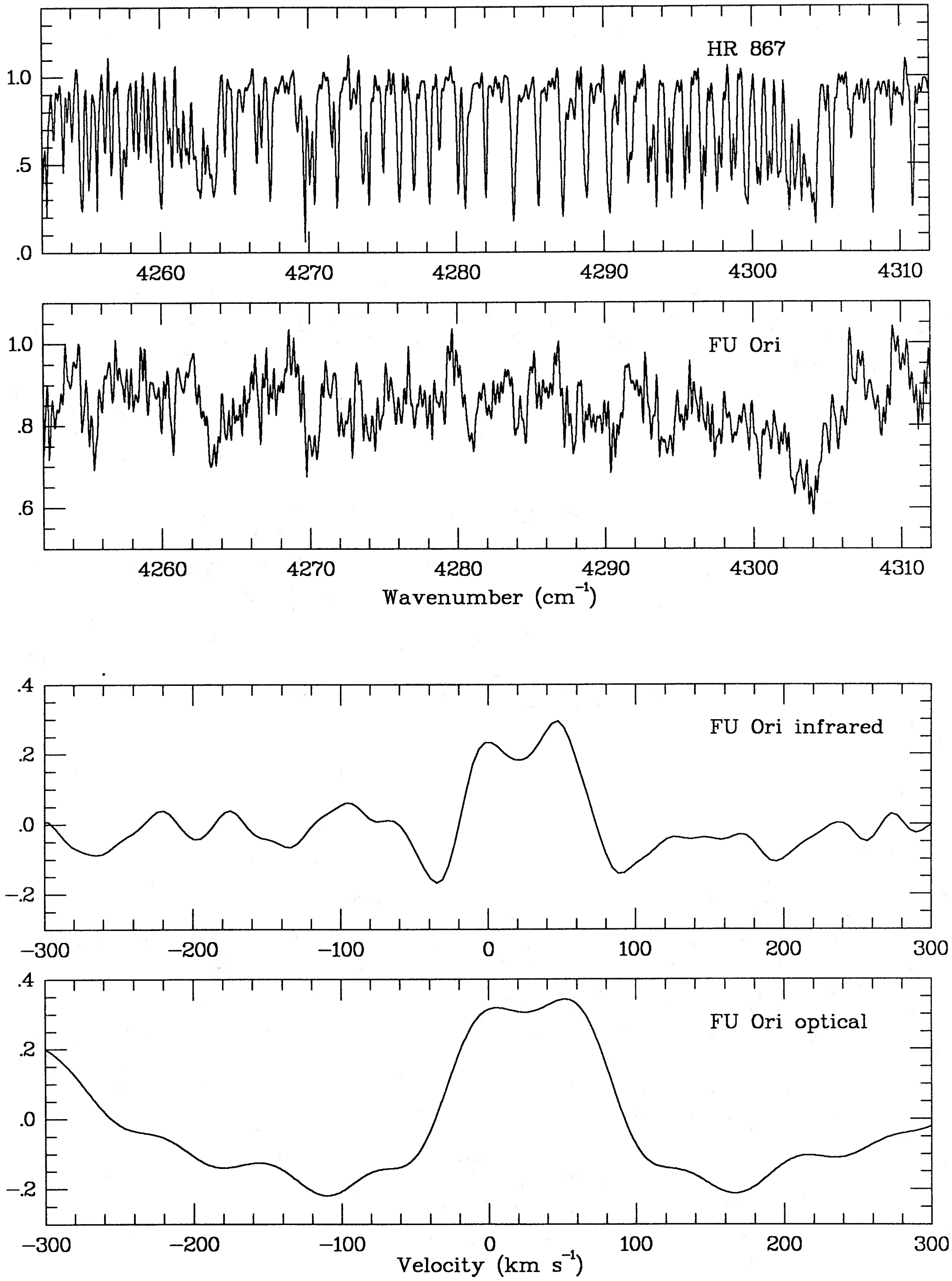

FIG. 1.—Rotation of FU Ori. *Upper two panels:* infrared FTS spectra of the M6 III star HR 867 and FU Ori. The v'–v'' 3–1 band head of ^{12}CO is seen near 4304 cm^{-1}. These spectra have been divided by a spectrum of the B star γ Ori taken at a similar airmass in order to minimize the effects of telluric lines. The CO lines of FU Ori are clearly broader than those of HR 867. *Third panel:* the cross-correlation of the HR 867 and FU Ori spectra shown in the upper two panels. The cross-correlation peak is quite broad, indicating rapid rotation in FU Ori. The cross-corrleation peak also appears doubled, as predicted by the accretion disk model. Tests indicate the cross-correlation peak at +45 km s^{-1} heliocentric velocity is not produced by telluric lines. *Bottom panel:* the cross-correlation of the sum of all 6170 Å spectra of FU Ori. The rotational broadening is larger at 6170 Å than at 2 μm. The central heliocentric velocity indicated by both correlations agrees with previous measurements from optical spectra and is also consistent with the velocity of neighboring interstellar material.

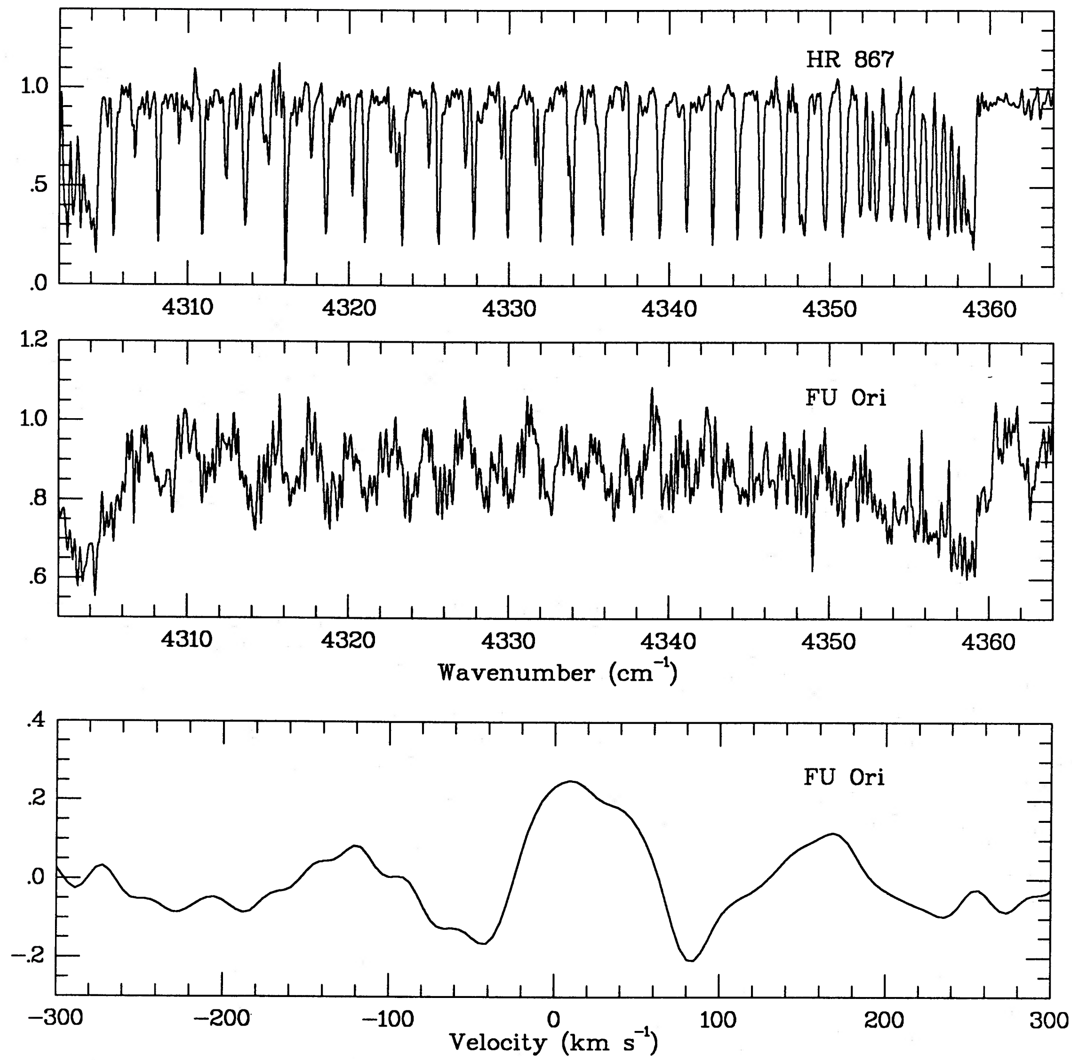

FIG. 2.—Same as the upper three panels in Fig. 1, except for the infrared spectral region including the v'–v'' 2–0 band head near 4360 cm^{-1}. In this case, the cross-correlation peak is asymmetric and exhibits a blueshift of 10 km s^{-1} relative to velocities obtained in other regions. This suggests that mass loss is affecting the v'–v'' 2–0 line profiles.

above, and that the radial velocity is consistent with that measured from the 3–1 overtone region.

b) FU Orionis: Optical Profiles

In Paper I we noted that Herbig and Petrov (1986) had reported doubled line profiles in one optical spectrum of FU Ori. Later spectra have not confirmed line doubling (Herbig 1986). Our spectra of FU Ori in Paper I did not show convincing evidence for doubled line profiles, but it was apparent that the effects of mass loss severely perturbed our results from the 5200 Å echelle order.

We have subsequently obtained new FU Ori spectra in the 6170 Å region. The lines in this region are much weaker than those in the 5200 Å echelle data. The correlation peaks are much less skewed toward negative velocities, indicating that the correlation is less affected by mass loss. The resulting correlation of the sum of all of our spectra with a standard template star is shown in Figure 1. The correlation peak is not as rounded as would be expected for a rotating sphere, but rather is flat or perhaps slightly dimpled on top. This structure is not strongly apparent in the individual lines present in the summed spectrum, as shown in Figure 3. In the optical cross-correlation shown in Figure 1, frequency components with periods <30 km s^{-1} have been filtered out. If higher frequency (noise?) components are left in, the "dimpling" of the correlation peak is less apparent (although tests with synthetically broadened template spectra demonstrate that our filtering *does not* artificially produce the central dip in the correlation peak). We conclude that the evidence for absorption line doubling in our optical spectra of FU Ori is weak.

c) V1057 Cygni and V1515 Cygni: Optical Profiles

In Paper I we showed that there was evidence in red (6170 Å) spectra of V1057 Cyg for "double-peaked" absorption in the weak photospheric lines. The 6141.73 Fe I line appeared to be doubled in our strongest exposure, and cross-correlation analysis of three individual spectra produced double-peaked correlations. We have now obtained several more spectra in this wavelength region to test the repeatability of this effect.

In Figure 3 we display the sum of all of our 6170 Å spectra taken with the MMT and the 1.5 m telescope for V1057 Cyg. Our previously published spectra of V1057 Cyg (Paper I)

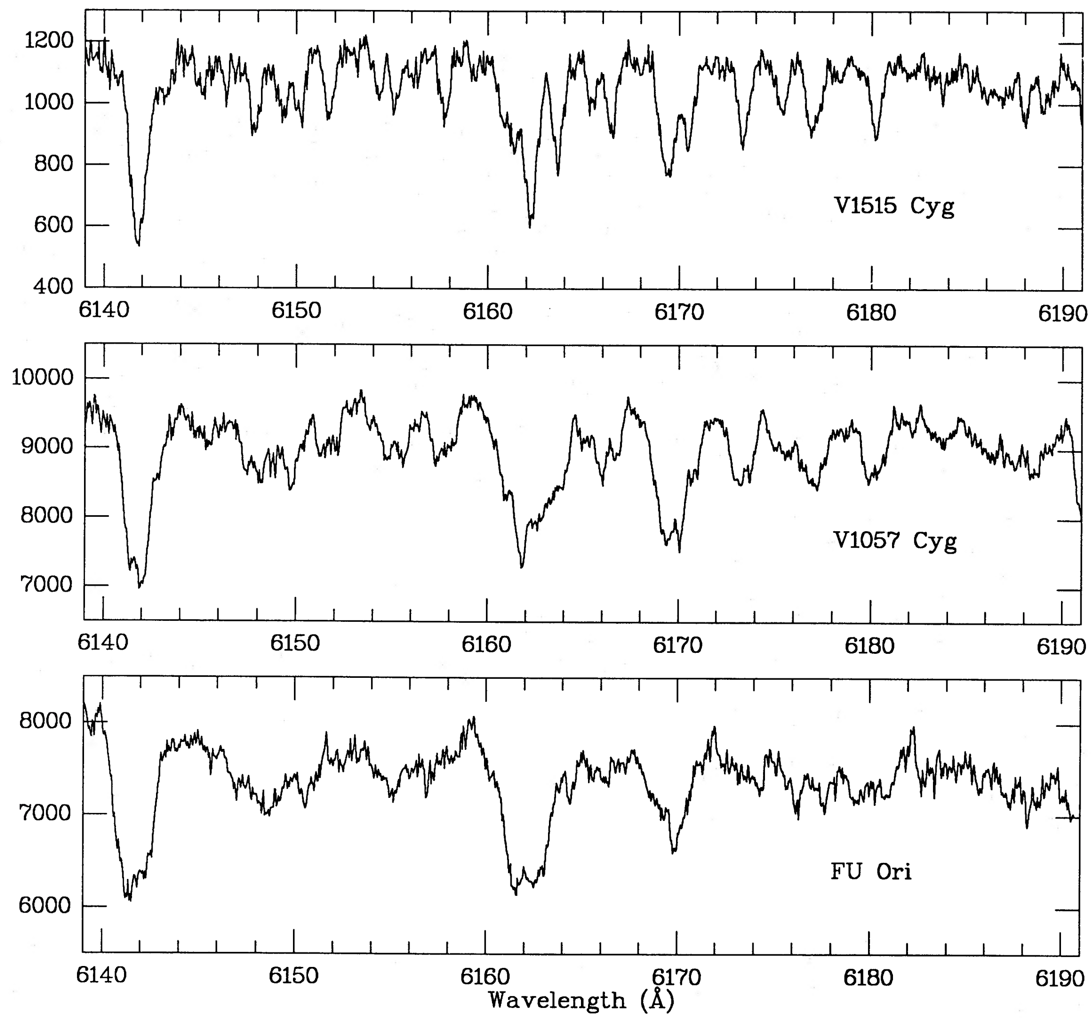

FIG. 3.—Sum of all MMT and 1.5 m echelle spectra for FU Ori, V1057 Cyg, and V1515 Cyg, taken over a period of approximately 1 yr. Appropriate heliocentric velocity shifts have been introduced to compensate for Earth's motion for the different exposure times. The spectra have been divided by a cubic polynomial to compensate for the echelle blaze and therefore rectify the continua. Count levels shown are approximately correct for regions near the center of the spectrum; at each end, the true count levels may be a factor of 2 smaller. The spectrum of V1515 Cyg provides a convenient example of a slowly rotating object. The 6141.73 Å Fe I line in V1057 Cyg shows a peculiar reversal, as found in Paper I. There are also suggestions of doubling in the profiles of other lines at 6147.8 Å (Fe I + Fe II), 6151.62 Å (Fe I), 6157.73 Å (Fe I), 6166.0 Å (Ca I), presumably related to the double structure seen in the cross-correlation peaks (Fig. 4). The FU Ori spectrum was used to produce the cross-correlation shown at the bottom of Fig. 1. There is evidence for a blueshifted "shell" (i.e., wind) feature in the 6141.73 Å line.

account for about one-third of the total counts accumulated so far. In addition to the 6141.73 Å Fe I line, there are indications of doubling in some other, weak lines, as can be seen by comparison with the spectrum of the slowly-rotating V1515 Cyg ($v \sin i \approx 20$ km s^{-1}).

The 6141.73 Å line does not always appear doubled in our new spectra of V1057 Cyg. However, cross-correlation analysis almost always indicates double-peaked structure, as shown in the montage presented in Figure 4. The cross-correlations for six of our seven new spectra are doubled. The one cross-correlation that does not show double structure results from one of the two weakest exposures taken. When added to our original three spectra shown in Paper I, which all had double cross-correlation peaks, we find evidence for line doubling in nine out of 10 independent spectra. This repeatability is too high to be coincidental. Double structure is not usually apparent in the correlations of 5200 Å echelle spectra of V1057 Cyg, showing that double correlation peaks are not artificially produced by our analysis procedure.

Thus, our red spectra of V1057 Cyg provide additional evidence for double line profiles. Our results show that this profile structure is not always apparent in the strongest lines and is best revealed by cross-correlation analysis, which incorporates the profiles of many lines.

The correlation peak width for V1057 Cyg seems to have increased over a time scale of 1 yr (Fig. 5). This trend appears independently in the red and blue spectra. The meaning of this change is unclear.

d) Radial Velocities

Our usual method of measuring radial velocities is to find the center of a parabola fitted to the correlation peak (Hartmann *et al.* 1986). However, the correlation peaks of FU Ori are often not parabolic in shape. In particular, correlations of the 5200 Å echelle spectra have peaks skewed toward negative velocities, probably due to the effects of mass loss (see Paper I). This skewing shows up as a net blueshift of the radial

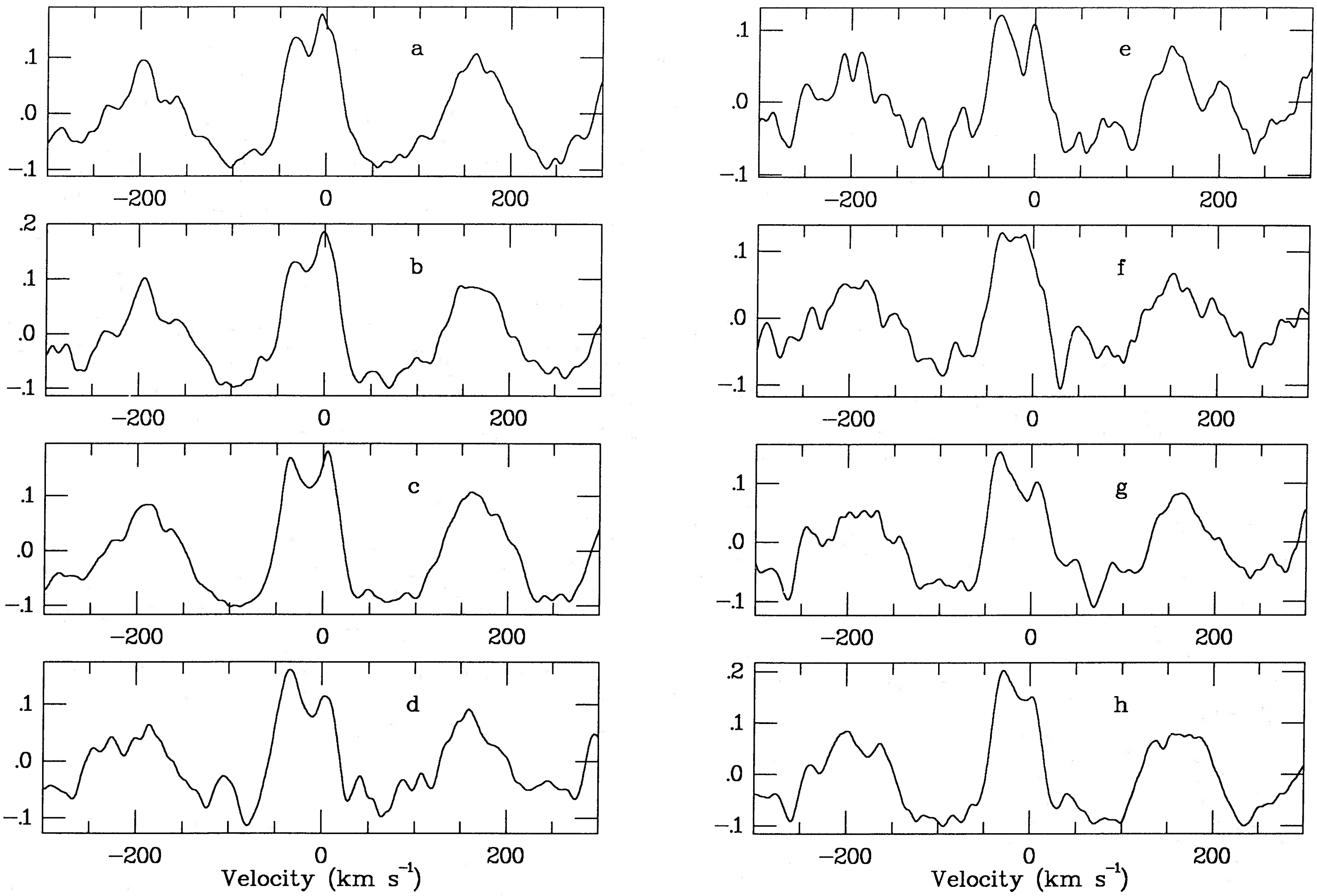

FIG. 4.—Montage of cross-correlations of 6170 Å spectra of V1057 Cyg. Dates of these spectra, given as numbers to be added to JD 2,446,000, along with maximum count levels, are as follows: (*a*) 361.58, 1200 counts; (*b*) 361.71, 900 counts; (*c*) 362.58, 2200 counts; (*d*) 390.58, 600 counts; (*e*) 391.66, 170 counts; (*f*) 392.57, 180 counts; (*g*) 392.61, 450 counts; (*h*) previously published in Paper I, JD 2,445,983.65, 2000 counts.

velocities measured with parabolic fits. The mean heliocentric radial velocity measured in this way from 14 5200 Å spectra is 22.6 ± 5.2 km s^{-1}, where the quoted error is the formal dispersion per observation. In contrast, the radial velocity measured from seven 6170 Å spectra is 29.2 ± 2.4 km s^{-1}.

To minimize the skewing effects of mass loss on the radial velocities measured from our blue (5200 Å) spectra, the radial velocities were defined by the average of the zero crossings of the correlation peak. This procedure results in measared radial velocities of 26.2 ± 2.2 km s^{-1} from 14 blue spectra and 27.9 ± 2.4 km s^{-1} from the seven red spectra.

In Figure 6 we present radial velocity results for our FU Ori spectra versus time. There is no evidence for radial velocity variability $\gtrsim 3$ km s^{-1}, which is certainly at the level of our errors, and that the velocities agree quite well with the heliocentric velocities of 27–28 km s^{-1} for interstellar material in the vicinity (Herbig 1977).

A similar graph for V1057 Cyg is shown in Figure 7, in which the radial velocities have been measured in the same way as for FU Ori. There is no obvious trend in radial velocity over a time period of 1 yr, and the scatter is comparable to our expected errors. The mean heliocentric velocity of about -16 km s^{-1} is reasonably consistent with Herbig's (1977) value of about -14 km s^{-1} and is close to the velocity inferred from a variety of measurements of nearby interstellar material (Herbig 1977).

Because no double correlation peak structure is seen for V1515 Cyg, we used parabolic fitting to measure the radial velocities for this object shown in Figure 8. The scatter is consistent with our expected measurement errors. No obvious trend can be discerned, and the radial velocity appears to be constant to within ± 2 km s^{-1}. The average radial velocity is about -14 km s^{-1}, reasonably consistent with the value of -12 ± 2 km s^{-1} obtained by Herbig (1977) and with the heliocentric velocity of -12 km s^{-1} given for the CO emission around a nearby star (Loren, Vanden Bout, and Davis 1973; Knapp *et al.* 1977).

III. DISCUSSION

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

As indicated in Figure 1, the line broadening in the infrared spectral region of FU Ori is substantially smaller than the optical line broadening. We use the widths of the cross-correlation peaks to measure this effect quantitatively. The level at which to measure the correlation peak width is somewhat arbitrary. We adopted widths at the zero level of the correlation; the results are not very sensitive to this choice.

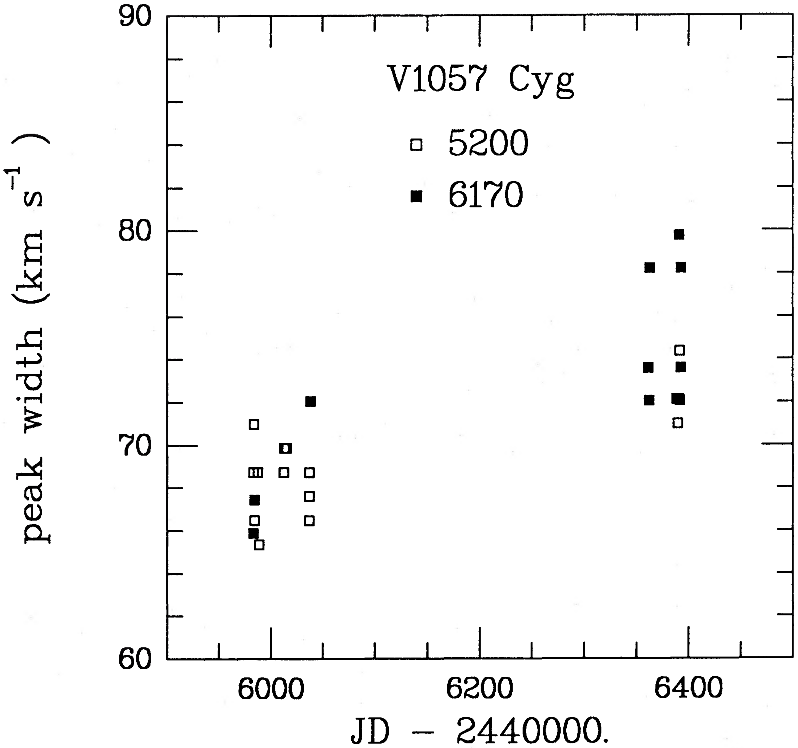

FIG. 5.—Full width at zero level for cross-correlation peaks of V1057 Cyg. Line widths appear to have increased on a time scale of a year.

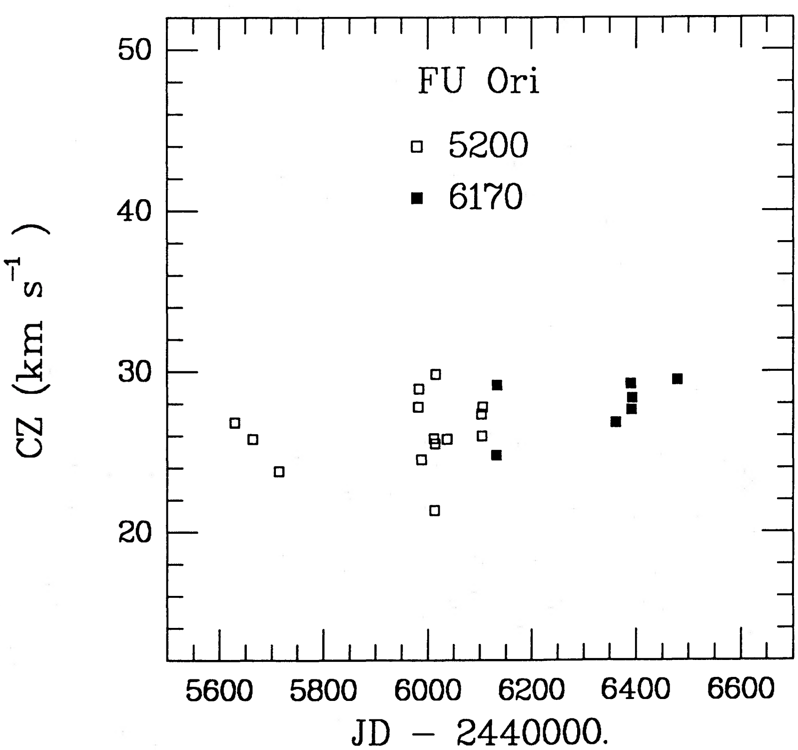

FIG. 6.—Measured radial velocities for FU Ori vs. time. The scatter is consistent with measurement error for this rapid rotator.

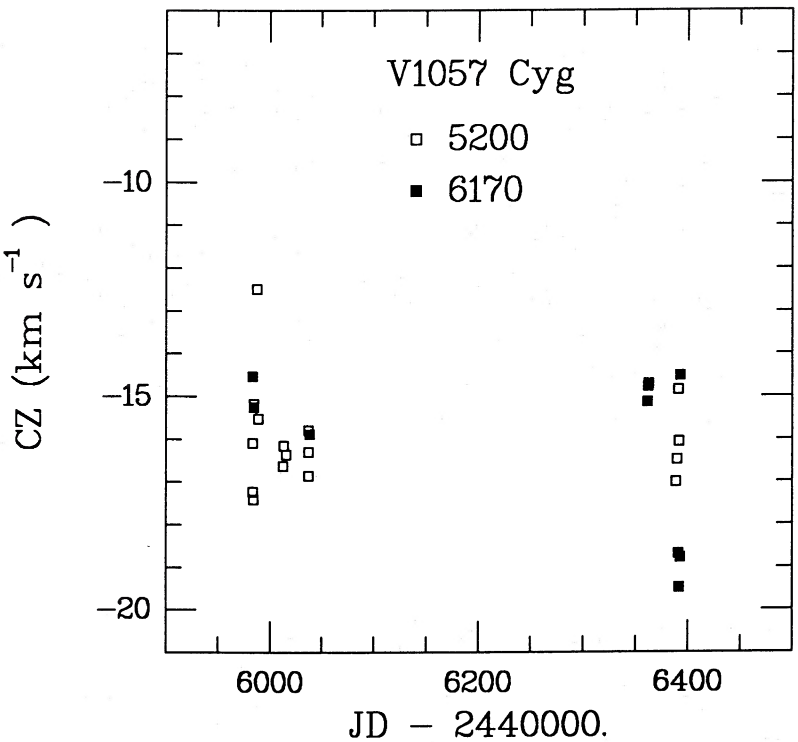

FIG. 7.—Radial velocities for V1057 Cyg vs. time. The expected measurement error per observation is $\sim \pm 3$ km s^{-1}.

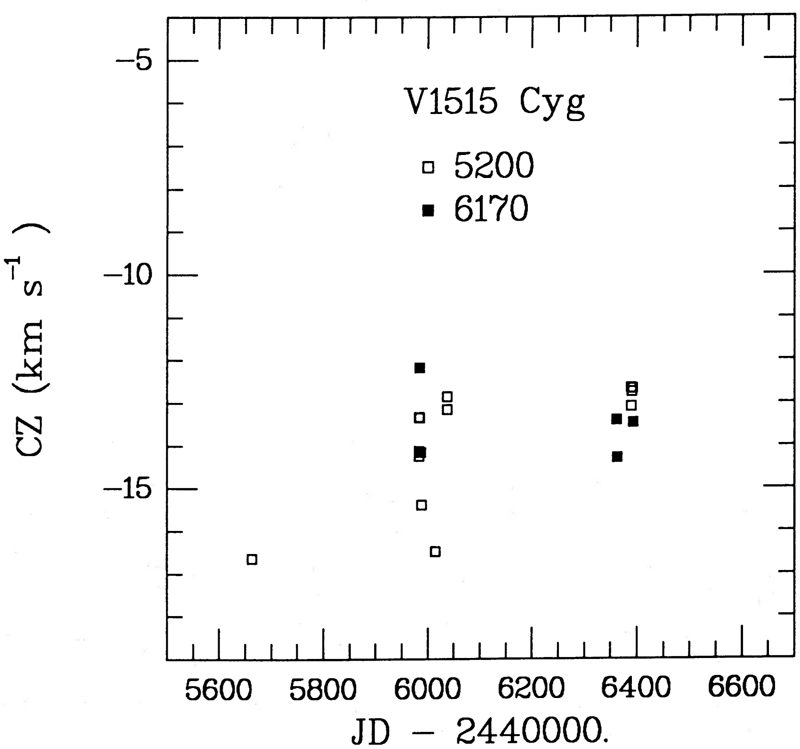

FIG. 8.—Radial velocities for V1515 Cyg. The scatter is generally consistent with expected measurement errors of ± 2 km s^{-1}.

TABLE 1

ROTATIONAL VELOCITIES FOR FU ORIONIS

Spectral Region	ΔV (km s^{-1})[a]
4300–4360 cm^{-1}	86.0 ± 2.5[b]
4250–4310 cm^{-1}	94.3 ± 1.6[b]
6170 Å	130 ± 3[c]
5200 Å	110 ± 6[d]

[a] Defined as full width of the cross-correlation peak at zero level.
[b] Mean of two exposures.
[c] Mean of seven exposures.
[d] Mean of 14 exposures.

Table 1 presents cross-correlation peak widths in different wavlength regions measured at the zero level of the correlation. In all cases the infrared correlation peaks are narrower than the optical correlation peaks. The 5200 Å (blue) correlation peak widths are systematically smaller than the corresponding widths measured in the 6170 Å (red) region. However, as shown in Paper I, and as discussed in the prior section on radial velocities, the 5200 Å cross-correlations generally exhibit blue asymmetries presumably produced by mass loss. Because the photospheric lines in the 5200 Å region are systematically stronger than lines in the 6170 Å region, the blue spectra are much more likely to be affected by lines formed in an outer expanding shell or wind. This expectation is confirmed by the greater asymmetry of the blue correlation peaks relative to the red correlation peaks. Thus, we consider the 6170 Å results to be the most reliable estimators of optical photospheric rotation.

Similarly, the blueshift of the CO 2–0 overtone region relative to the 3–1 overtone region indicates that the 3–1 region is the least disturbed by mass loss. Therefore we compare the 3–1 infrared region results with the 6170 Å correlations to arrive at a best estimate for the ratio of infrared to optical rotational velocities in FU Ori of about 0.73.

We next estimate the wavelength dependence of rotation predicted by the disk model. The line profiles from a disk are conceptually the sum of contributions from different annuli, each having a different surface brightness, spectrum, and projected rotational velocity. In principle, one would represent each disk annulus spectrum by the observed spectrum of a star with the appropriate effective temperature and surface gravity. The summed spectrum could then be cross-correlated in the same way as our real spectra, and the cross-correlation peaks compared. However, at present we do not have a suitably extensive library of optical high-resolution standard star spectra. The use of blackbody fluxes to represent the spectra of disk regions with surface temperatures $\lesssim 2000$ K introduces further uncertainty.

For an initial attack on the problem we have adopted a simpler method. Stellar observations indicate the line strengths in the 6170 Å and 2 μm regions are not highly variable within certain effective temperature limits. We therefore consider the profile produced for a line which does not vary in equivalent width within a given temperature range, but has zero equivalent width outside that range. We have ignored contributions to the 6170 Å spectrum from disk regions below 3300 K and contributions to the 2 μm region from regions hotter than 5300 K. The latter temperature cutoff is based on the disappearance of CO lines in early G supergiant stars.

The steady disk model we use was presented in Paper I, along with details concerning its derivation (cf. Shakura and Sunyaev 1973; Lynden-Bell and Pringle 1974). Although the model was originally developed to represent V1057 Cyg in detail, if we assume $R_* = 6\,R_\odot$, $d = 500$ pc, and $E(B-V) = 0.7$ (Paper I), the model roughly reproduces the observed V magnitude and colors of FU Ori.

In Figure 9 we have plotted the average line profiles predicted by the disk model in the 6170 Å and 2.2 μm regions, convolved with the appropriate instrumental broadening. Comparison with the correlation peaks indicates that the model predicts a ratio of widths $\sim 20\%$ larger than observed in the correlation peaks. However, one must consider at least three sources of error in the model. (1) The line equivalent widths are not independent of effective temperature. Tests changing the weights of different temperature annuli to reproduce roughly the variation of equivalent widths for the strongest lines suggests that this effect might change the optical correlation peak width by 10% or more. (2) Half of the light at 2.2 μm comes from regions cooler than 2700 K, for which we use blackbody fluxes in the absence of appropriate standard stars. (3) Radiative transfer effects in the turbulent atmosphere of FU Ori may be responsible for the absence of strong double structure in the optical line profiles, and therefore may affect the overall line widths. Given these complications, we conclude that the observations are in reasonable agreement with the disk model.

a) Alternatives to the Disk Model

We have shown that the disk model accounts for evidence of double-peaked profiles in the infrared spectrum of FU Ori and in the optical spectra of V1057 Cyg. The disk model also predicts that the rotation of FU Ori in the infrared should be slower than in the optical, as observed. Taken in conjunction with the disk model's ability to account for the observed variation of spectral type with wavelength and the outburst energetics and rise times, the case for pre–main-sequence disk accretion in FU Ori objects is strong. However, it is important to consider whether other models might also account for the observations.

An alternative model explored in Paper I hypothesized mass transfer from a companion "M giant" filling its Roche lobe. In this case, the Roche lobe region would account for the infrared spectrum and might be rotating rapidly due to tidal synchronization. Limits on optical radial velocity variability suggested that the mass ratio should be <0.4. As shown in Paper I, radial velocity variations of the infrared spectrum should be 10 km s^{-1} or so unless the mass ratio is <0.01. Although the time coverage of the infrared data is limited, observations of FU Ori at three different epochs (a low-dispersion archival FTS spectrum taken in 1979 October was made available by K. Hinkle) show no evidence for radial velocity variability >3 km s^{-1}. Since it is also difficult to understand the evolutionary status of an "M giant" presumably paired with a T Tauri star, the binary model is unappealing.

In a personal communication, J. Elias and S. Strom questioned whether a variant of the disk model is possible in which the infrared emission comes from an extended disk but the optical spectrum arises from a central G-type star. We think this model is less plausible than our picture because the G-type "object" must be rotating nearly at breakup velocity. Our argument is as follows. If the infrared spectrum arises in a disk then presumably its $v \sin i$ is equal to the local Keplerian velocity. From the observed energy distribution, an estimate of

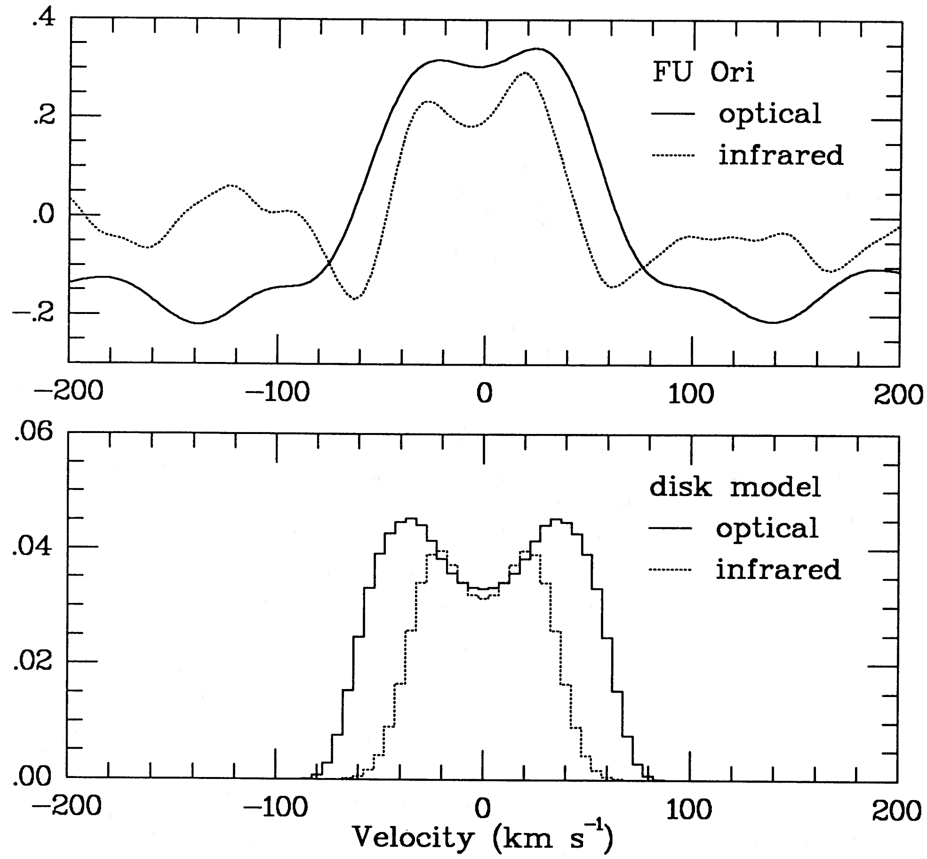

FIG. 9.—Comparison of observed (*top panel*) correlation peaks for FU Ori with the model line profiles predicted for the accretion disk model (*bottom panel*). Only the velocity width ratio of the disk model profiles is meaningful; the overall velocity widths have been scaled to achieve the best match with observation. The observed infrared rotational velocity is smaller than the optical rotation, as expected for a differentially rotating, luminous accretion disk.

the reddening, and blackbody arguments one can estimate the relative areas emitting in the infrared and in the optical. This analysis shows that the G-type object must be much smaller than the infrared-emitting object. The observed ratio of rotational velocities then implies that the G-type object must also be rotating approximately at breakup velocity. This result is consistent with the optical cross-correlations of V1057 Cyg, whose double peaks suggest emission from a highly flattened, rotating surface.

It is hard to envision a process changing the internal structure of the initial star which yields a G supergiant star rotating at breakup after outburst, since it would seem that the optical component must have *expanded* during outburst (Herbig 1977). Furthermore, the G supergiant model provides no obvious explanation for the outburst energy. On the other hand, the disk model proposed in Paper I naturally explains the rapid rotation of the optical spectrum, and provides a mechanism for producing the optical outburst.

c) Estimated Disk and Central Object Properties

We next consider the implications of the disk model for the nature of the central object and its environment. Several parameters characterize a steady disk model: the central mass, M; the accretion rate, $\dot{M}$; the radius of the central object (and the inner radius of the disk), R; and the inclination of the disk rotational axis to the line of sight, i. Assuming that the distance estimates of Herbig (1977) are approximately correct, the luminosity can be estimated. With extinction corrections for FU Ori objects one can estimate the characteristic disk temperature, which is proportional to $M\dot{M}/R^3$. From the luminosity and the characteristic temperature, one can estimate $R(\cos i)^{1/2}$, and hence $M\dot{M}(\cos i)^{3/2}$.

For FU Ori we adopt the disk model given in Paper I, adopting an $E(B-V)$ of 0.7 and a distance of 500 pc (Herbig 1966). Assuming $i = 50°$, we find $R \approx 6\ R_\odot$ and a product of $M\dot{M} \approx 1.4 \times 10^{-4}\ M_\odot{}^2\ \mathrm{yr}^{-1}$. Beyond the uncertainty in i, it would not be unreasonable to expect a 20% uncertainty in the distance and an error of ± 0.1 mag in $E(B-V)$. Thus, the uncertainty in R could easily be 30%, corresponding to a factor of 2 uncertainty in $M\dot{M}$, independent of the inclination.

FU Ori is situated near the apex of a roughly fan-shaped reflection nebulosity (cf. Dieckvoss 1939; Herbig 1966). Study of Dieckvoss's early picture, which is not as overexposed as many later ones, suggests that the fan-shaped nebula might be the projection of a roughly conical reflecting surface resulting from a flaring disk-shaped distribution of material. The picture suggests that we are observing FU Ori from just over the edge of this surface. Adopting this view, and assuming that the nebula is symmetric, from the opening angle of the fan-shaped reflection nebula of $\sim 100°$–$110°$ we estimate $i \approx 50°$. The observed optical rotation, combined with the radius estimate $R = 6\ R_\odot$, then implies $M \approx 0.6\ M_\odot$. While this result is subject to the uncertainties in R estimated above and is clearly sensitive to details of the adopted geometrical picture, it is suggestive that the derived mass is comparable to that estimated for typical T Tauri stars (cf. Cohen and Kuhi 1979). The identification of FU Ori with a low-mass central object is also consistent with Herbig's (1977) characterization of the pre-outburst spectrum of V1057 Cyg as that of a typical T Tauri star.

Adoption of this inclination and central mass for FU Ori implies an accretion rate of $\sim 2 \times 10^{-4}\ M_{\odot}\ \mathrm{yr}^{-1}$, so that FU Ori has accreted $10^{-2}\ M_{\odot}$ since outburst. Despite the uncertainties involved with these estimates, it is difficult to escape the conclusion that the accretion outburst of FU Ori has had a significant impact on the evolution of the central star.

d) *Importance of FU Orionis Events*

Herbig (1977) suggested that, in order to understand the frequency of observed FU Ori events, it was necessary to suppose that each T Tauri star undergoes many outbursts in its lifetime, spaced by perhaps 10^4 yr. In Paper I we estimated the total number of candidate stars in an entirely different way than Herbig, and also concluded that FU Ori events must be repetitive. If FU Ori events consist of the accretion of 10^{-3} to $10^{-2}\ M_{\odot}$, and a T Tauri star undergoes 10^2 such events in its lifetime (Herbig 1977), one is led to consider whether a large fraction of the central star is built up by disk accretion (cf. Mercer-Smith, Cameron, and Epstein 1984).

We address this problem in the following way. The estimated distances for FU Ori and V1057 Cyg are $\sim$500–600 pc and $\sim$1000 pc for V1515 Cyg (Herbig 1977); Elias 12 is estimated to be at $\sim$900 pc (Elias 1978); and the distance of the object associated with HH 57 is very crudely estimated to be $\sim$700 pc (Graham and Frogel 1985). We suppose that all recent FU Ori events within a 1 kpc radius of the Sun have been observed. Assuming that the central objects have masses $\sim 0.5\ M_{\odot}$, we use the results of Paper I to estimate peak accretion rates in FU Ori objects $\sim 10^{-4}\ M_{\odot}\ \mathrm{yr}^{-1}$. This rate implies that approximately $4 \times 10^{-4}\ M_{\odot}\ \mathrm{yr}^{-1}$ is being accreted presently in FU Ori events within a 1 kpc distance of the Sun. Miller and Scalo (1979) estimated the star formation rate in the solar neighborhood as $\sim 3\text{–}7 \times 10^{-9}\ M_{\odot}\ \mathrm{pc}^{-2}\ \mathrm{yr}^{-1}$. Thus, the total star formation rate within 1 kpc of the Sun is $\sim 1\text{–}2 \times 10^{-2}\ M_{\odot}\ \mathrm{yr}^{-1}$. If every (low-mass) star is subject to FU Ori events, the ratio of the star formation rate to the estimated accretion rate implies that each star accretes a few percent of its mass in this way.

It is likely that we have not detected all the FU Ori events within this volume, considering the large extinctions of molecular clouds. If all stars undergo FU Ori accretion, it is conceivable that as much as 10% of the final star is accreted from the disk. Alternatively, if only a small fraction of (low-mass) stars undergo FU Ori accretion for some reason, these stars might accrete most of their mass from a disk. However, it seems unlikely that most stars accrete most of their mass in FU Ori events, because one would have to invoke a large incompleteness factor for discovery of ~ 50. Surveys for luminous embedded infrared sources may be able to constrain this possibility further.

e) *Disk Wind*

In Paper I we suggested that the mass loss indicated by P Cygni Hα and Na I profiles in FU Ori objects arises from the optical disk surface. As discussed in § II, we have evidence for blueshifted material in the CO v'–v'' 2–0 vibrational transitions seen in the 2 μm region. It seems unlikely that this blueshifted material arises from a diverging flow from the central regions seen in projection against the outer disk. If this were really the case, one would expect to see broad absorption components blueshifted to higher velocities, since wind velocities indicated by optical lines are $\sim$100–300 km s^{-1}. A much more probable interpretation is that the blueshifted CO arises in regions close to the disk, which have just begun accelerating perpendicular to the disk and so have low velocities. Thus we argue that the blueshifted CO lines provide additional evidence for a disk wind.

IV. SUMMARY

Our observations show that FU Ori rotates rapidly at 2 μm, but more slowly than at 6170 Å. This differential rotation is predicted by the accretion disk model for FU Ori outbursts. Optical observations of V1057 Cyg provide additional evidence for double-peaked profiles, another disk model prediction. The disk model also naturally accounts for a wide variety of phenomena associated with FU Ori objects, as discussed in Paper I. Taking all of these factors into consideration, the case for the accretion disk model is strong.

In the absence of evidence for radial-velocity variability $\gtrsim 3$ km s^{-1} in either the optical or infrared regions, we conclude that the accretion disk is not fed by a companion star, but rather consists of remnant material from the star formation process. Fairly crude statistical arguments suggest that low-mass stars accrete $>1\%$ (perhaps as much as 10%) of their mass in FU Ori events.

We wish to acknowledge the able and very necessary assistance of Ken Hinkle in obtaining the 4 m FTS data. Rob Hewett reduced most of the data presented in this paper and produced the figures. We also acknowledge useful conversations with J. Elias and S. Strom. This work was supported in part by the Scholarly Studies program of the Smithsonian Institution.

REFERENCES

Brault, J. W., and White, O. R. 1971, *Astr. Ap.*, **13**, 169.
Cohen, M., and Kuhi, L. V. 1979, *Ap. J. Suppl.*, **41**, 743.
Dieckvoss, W. 1939, *Beob. Zirk.*, **21**, 30.
Elias, J. 1978, *Ap. J.*, **224**, 453.
Graham, J. A., and Frogel, J. A. 1985, *Ap. J.*, **289**, 331.
Hartmann, L., Hewett, R., Stahler, S., and Matthieu, R. D. 1986, *Ap. J.*, **309**, 275.
Hartmann, L., and Kenyon, S. J. 1985, *Ap. J.*, **299**, 462 (Paper I).
Herbig, G. H. 1966, *Vistas Astr.*, **8**, 109.
———. 1977, *Ap. J.*, **217**, 693.
———. 1986, private communication.
Herbig, G. H., and Petrov, P. 1986, in preparation.
Knapp, G. R., Kuiper, T. B. H., Knapp, S. L., and Brown, R. L. 1977, *Ap. J.*, **214**, 78.
Latham, D. W. 1982, in *IAU Colloquium 67, Instrumentation for Astronomy with Large Optical Telescopes*, ed. C. M. Humphries (Dordrecht: Reidel), p. 259.
Loren, R. B., Vanden Bout, P. A., and Davis, J. H. 1973, *Ap. J.* (*Letters*), **185**, L67.
Lynden-Bell, D., and Pringle, J. E. 1974, *M.N.R.A.S.*, **168**, 603.
Mercer-Smith, J. A., Cameron, A. G. W., and Epstein, R. I. 1984, *Ap. J.*, **279**, 363.
Miller, G. E., and Scalo, J. M. 1979, *Ap. J. Suppl.*, **41**, 513.
Mould, J. R., Hall, D. N. B., Ridgway, S. T., Hintzen, P., and Aaronson, M. 1978, *Ap. J.* (*Letters*), **222**, L123.
Shakura, N. I., and Sunyaev, R. A. 1973, *Astr. Ap.*, **24**, 337.

L. Hartmann and S. J. Kenyon: Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138