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ON THE NATURE OF FU ORIONIS OBJECTS[1]

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ABSTRACT

We argue that rapid accretion onto pre–main sequence stars causes the outbursts of FU Orionis objects. In our model, emission from the hot, optically thick accretion disk dominates the system light at maximum. The radial temperature gradient of the disk produces an M-type spectrum in the infrared, a G-type spectrum at optical wavelengths, and an excess below 4000 Å, as observed. The absence of detectable radial velocity variations leads us to suggest that the accreted material comes from a surrounding protostellar nebula, rather than a companion star.

A crucial prediction of the disk model is that weak absorption lines should be double-peaked. We report high-resolution spectra of V1057 Cyg which show double-peaked profiles in red photospheric lines. Herbig and Petrov have observed a similar effect in FU Ori, indicating that doubled profiles are characteristic of FU Orionis objects. In principle, the double absorption might be produced by a spectroscopic binary system, but the orbital period of such a system must be short, and no evidence for velocity-crossing has yet been observed.

We further propose that the observed massive winds of FU Orionis objects arise from the luminous disk surface. The large occultation of redshifted material implied by this picture is in agreement with the meager redshifted emission observed in the Hα P Cygni profiles of these objects. Bipolar outflows have been associated with a number of pre–main sequence stars; we point out that ejection from a disk can naturally and efficiently produce winds with the appropriate geometry.

Subject headings: line profiles — stars: accretion — stars: mass loss — stars: pre–main-sequence

I. INTRODUCTION

The FU Orionis objects are among the most remarkable variable stars known. The two best studied members of the class, FU Ori and V1057 Cyg, have undergone spectacular increases in visual brightness ($\Delta V \approx 5$–6 mag in $\lesssim 1$ yr) and have remained very luminous for years or even decades (Herbig 1977). The spectra of FU Orionis objects in outburst are peculiar. Observations in the optical spectral region indicate a rapidly rotating G supergiant (Herbig 1966, 1977), while near-infrared spectra exhibit absorption lines characteristic of M stars (Mould *et al.* 1978).

Larson (1980) has suggested that rapid rotation in an early stage of stellar evolution is the source of the outburst energy, based on the identification of the progenitors as low-mass, pre–main-sequence stars (Herbig 1966, 1977). Other proposals for the outburst mechanism include subsurface nuclear reactions and effects of strong magnetic fields (cf. Herbig 1977). However, none of these models account for the many peculiarities of FU Orionis variables in a simple way.

A number of authors have suggested that accretion is responsible for FU Orionis events (Paczyński 1976; Herbig 1977; Larson 1983; Lin 1985). In this paper, we also propose that FU Orionis eruptions are produced by accretion, and that a hot, optically thick accretion disk dominates the observed spectrum in outburst. We show that the accretion disk theory straightforwardly and quantitatively explains a number of peculiar observational features, including the energy source for the outburst, the rise time of the outburst, the ultraviolet excess, the M-type spectrum in the infrared, and the color evolution during decay from maximum light. Furthermore, the disk model predicts that weak photospheric lines should have double-peaked profiles, as observed in FU Ori by Herbig and Petrov (1985). We report new high-dispersion, high signal-to-noise ratio red spectra of V1057 Cyg which also show such double profiles.

The energy released in an FU Orionis event requires the accretion of $\sim 10^{-2}\ M_\odot$. Since there is no evidence for binary motion from present data, we suggest that a remnant protostellar nebula surrounding a young T Tauri star is the source of the accreted material. We examine the possibility that accretion disk instabilities similar to those proposed for dwarf novae outbursts (e.g., Osaki 1974; Cannizzo and Wheeler 1984, and references therein) are responsible for the sudden, rapid accretion in FU Orionis systems.

New spectroscopic and spectrophotometric observations of FU Ori, V1057 Cyg, and V1515 Cyg are presented in § II of this paper. In § III we discuss the difficulties associated with binary models and conclude that an accretion disk provides the most satisfying explanation of the observations. In § IV we consider the possibility that disk instabilities trigger the outbursts, and show that the rise times for accretion events are compatible with the optical light curves. Finally, in § V we suggest that winds from disks should have a bipolar geometry and consider the possible relationship between FU Orionis outbursts, bipolar flows, and Herbig-Haro objects.

II. OBSERVATIONS

a) Optical Spectrophotometry

Optical spectrophotometric observations of FU Ori were obtained on 1984 April 9 and 13 with the cooled dual-beam intensified Reticon scanner (IRS) mounted on the white spec-

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trograph of the KPNO No. 1 90 cm telescope. Observations of five or six standard stars were made each night to place the data on the Hayes and Latham (1975) flux scale; the standard deviations of the photometric calibration suggest the flux scale is accurate to ± 0.03 mag, while relative fluxes are somewhat better determined. The two FU Ori spectra (covering 3500–6100 and 5800–8400 Å) match precisely at 5800–6100 Å and have therefore been combined into the plotted spectrum shown in Figure 1. Strong H I and Na I absorption lines dominate this spectrum, and lines from Mg I and Ca II are also visible. This spectrum is similar to that described by Herbig; the system appears not to have evolved significantly since 1975–1976.

Spectroscopic classifications of FU Orionis stars are wavelength-dependent, with spectral types F5–F8 I–II characteristic of blue spectra ($\lambda\lambda$3500–5000) and G0–G5 I–II characteristic of red spectra ($\lambda\lambda$5000–7000). It is important to verify that the color temperature is also wavelength-dependent, which is obviously complicated by the large reddening toward these objects. To investigate this problem in detail, we first corrected the FU Ori spectra for extinction using Schild's (1977) reddening law and then divided this result by spectra of various F and G standard stars (Jacoby, Hunter, and Christian 1984). These divided spectra have been normalized to a mean value of unity ($\int F_\lambda d\lambda / \int d\lambda = 1$).

The results of this procedure, using three G0 stars of differing gravity as standards, are displayed in Figure 2. At wavelengths below 5000 Å, FU Ori exhibits a large excess over the G0 supergiant. Division by a higher gravity standard star reduces the short-wavelength excess (Fig. 2); adoption of a dwarf spectrum eliminates the excess entirely. However, one is then left with a peculiar hump in the divided spectrum in the region 4600–5200 Å. Thus, supergiant spectra provide a better representation of the flux distribution between 4000 and 7000 Å than do higher gravity stars, in agreement with spectral classifications (Herbig 1977).

As the spectral type of FU Ori is somewhat uncertain, we have divided the spectrum by standards of differing effective temperature, modifying the amount of extinction (E_{B-V} = 0.5–1.1) to produce a flat divided spectrum over the largest wavelength interval. The divided spectra using F6 and G2 supergiants shown in Figure 3 are typical of our results. In all cases a significant excess at wavelengths below 4000 Å persists. This conclusion is not an artifact of our flux calibration, as contemporaneous spectra of sdO stars are well calibrated (± 0.03 mag) over the interval 3500–8500 Å. Furthermore, it is not plausible that variations from the standard extinction laws can produce such a rapid increase in flux over the short-wavelength interval observed. There is no evidence that this excess is related to Balmer emission; the Balmer lines are mostly in absorption (cf. Herbig 1966), though there is strong Ca II H and K emission. We therefore conclude that the optical spectral energy distribution of FU Ori cannot be reproduced by a single normal star, and that a significant blue excess is present below 4000 Å, in agreement with Herbig's (1977) results for V1057 Cyg.

b) High-Resolution Spectra

We have obtained high-resolution observations of V1057 Cyg, V1515 Cyg, and FU Ori using the echelle spectrographs and intensified Reticon detectors on the MMT and the 1.5 m telescope of the Fred L. Whipple Observatory on Mount Hopkins. Details of the instrumentation are given by Latham (1982). Our observations were restricted to a 44 Å bandpass centered near 5200 Å and a 56 Å bandpass centered near 6170 Å. The spectral resolution of the data is approximately 12 km s^{-1}.

The absorption line velocities and profiles have been analyzed by cross-correlating the FU Orionis object spectra with the spectrum of a "template" star, following the methods of Tonry and Davis (1979). We found that template stars with

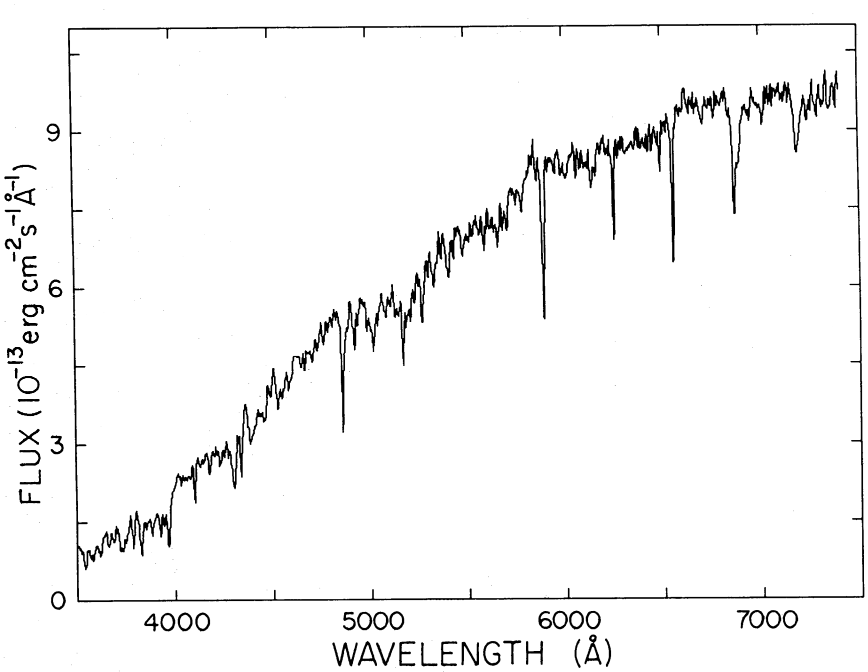

FIG. 1.—Low-resolution optical spectrum of FU Ori. Strong absorption lines from H I, Na I, and Mg I are intrinsic to this system; lines at 6850 Å and 7150 Å are terrestrial atmospheric features, while the line at 6250 Å is a bad pixel in the KPNO intensified reticon scanner.

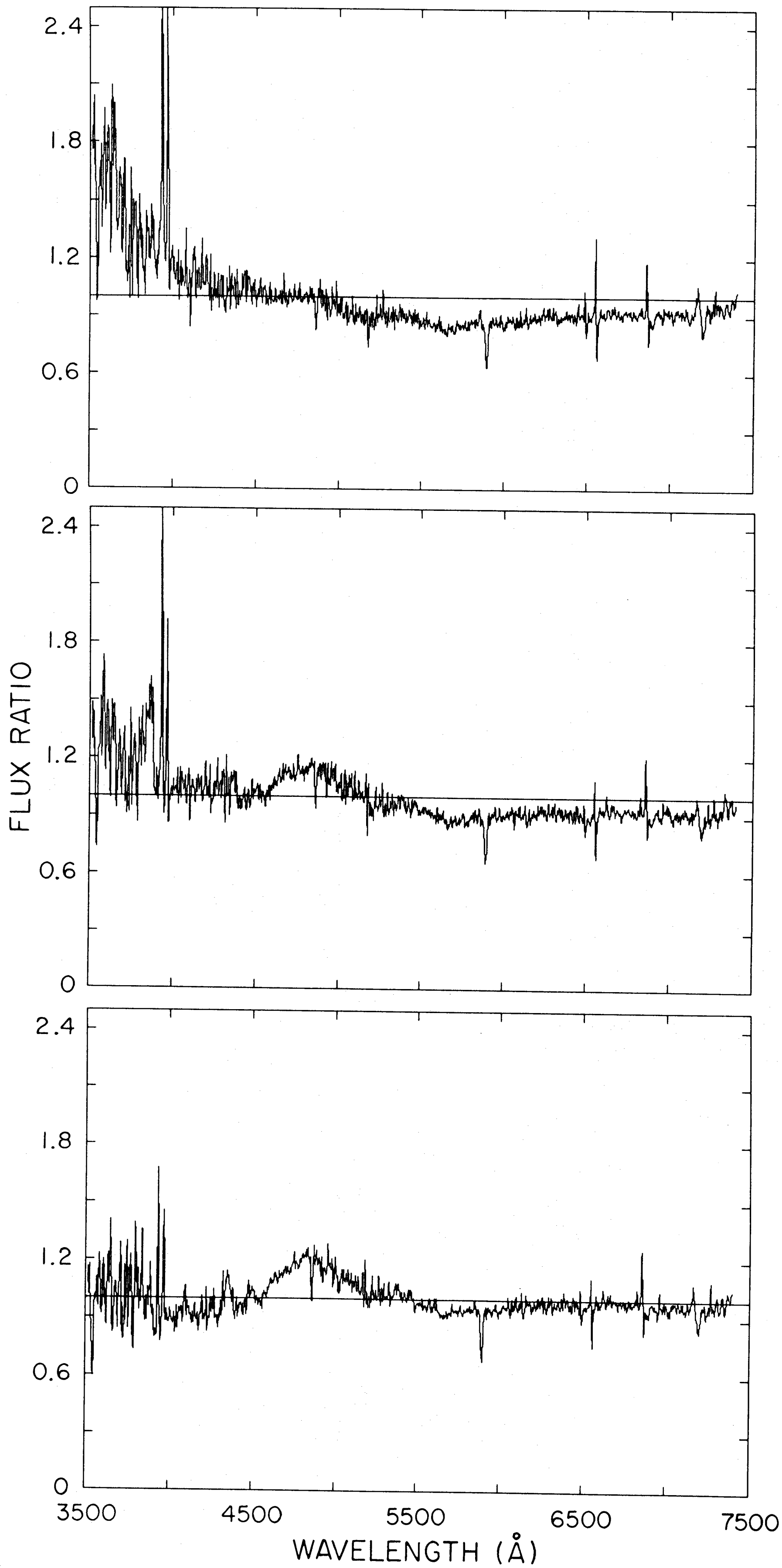

FIG. 2.—Flux ratios of FU Ori and various G0 standard stars (Jacoby, Hunter, and Christian 1984). The top panel is the result of dividing Fig. 1, dereddened by $E_{B-V} = 0.7$, by a G0 supergiant. The large UV excess in this spectrum can be reduced if FU Ori is dereddened by $E_{B-V} = 0.9$ and a G0 giant (*middle panel*) or a G0 main-sequence star (*lower panel*) is used as the standard, but this introduces a hump in the divided spectra at 4600–5200 Å. Thus, a G0 supergiant provides the best representation of FU Ori over 4000–7400 Å, in agreement with Herbig's (1977) classification.

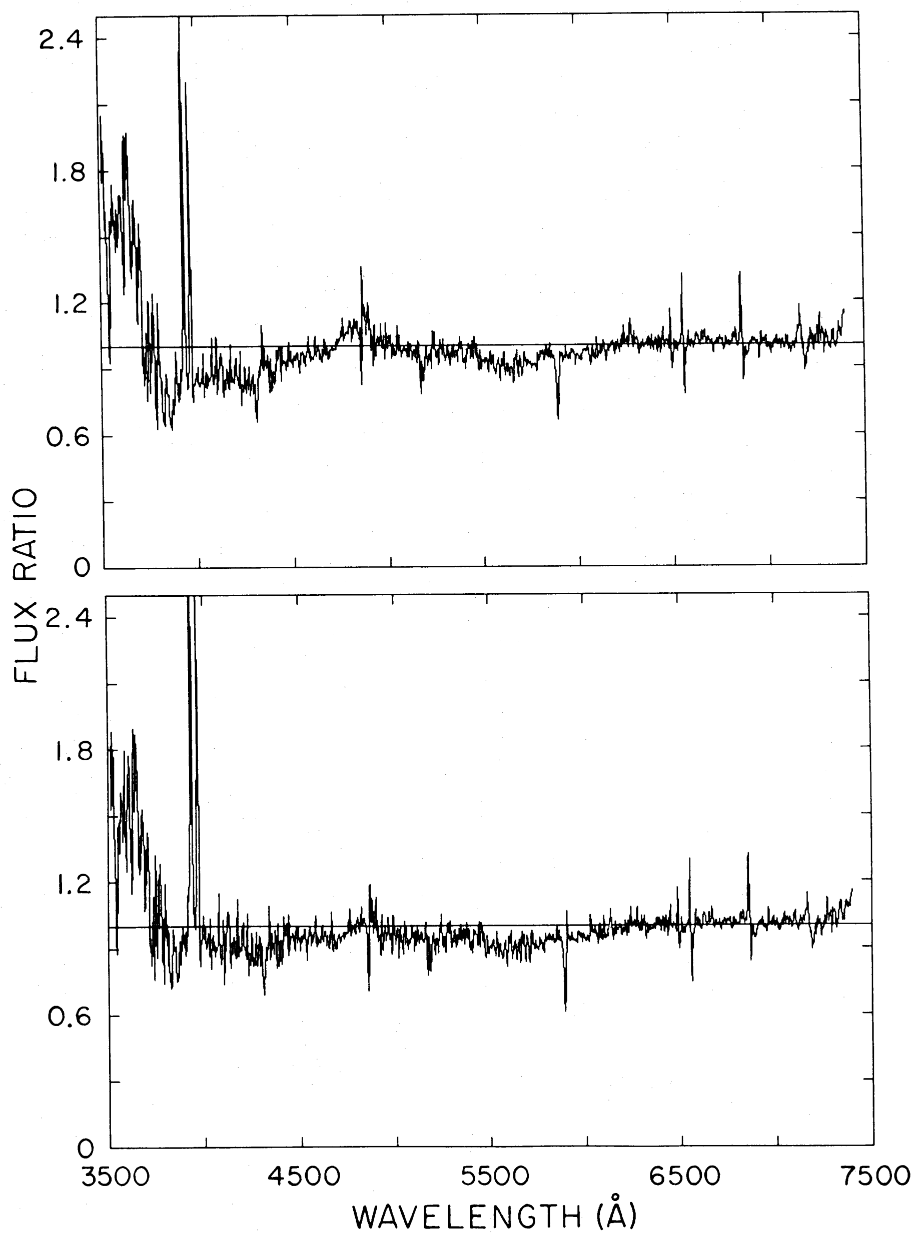

FIG. 3.—Flux ratios of FU Ori and (1) an F6 supergiant (*top panel*) and (2) a G2 supergiant (*lower panel*). The FU Ori spectrum has been dereddened by E_{B-V} = 1.1 and 0.5 respectively to construct these spectra, which demonstrate that a single standard star cannot adequately reproduce the FU Ori spectrum.

G spectral types provided higher signal-to-noise correlations than resulted from K-star templates; that is consistent with the G supergiant spectral types estimated by Herbig (1977). The velocity shifts and line widths derived from the cross-correlation are not sensitive to the choice of template.

Since the cross-correlation peak is significantly broader than the instrumental and template line widths for all the FU Orionis objects, the shape of the peak represents the "average" absorption line profile, with the stronger lines given greater weight. By using the cross-correlation analysis we can determine the average line profile with more accuracy than would be possible for a single line, and the method also allows for the effects of line overlap or blending.

Parabolic least-squares fits to the upper half of the cross-correlation peak were used to determine the velocity shift of the peak and hence the radial velocity of the object. Features, broader than about 150 km s^{-1} in the V1057 and V1515 Cyg spectra, and broader than about 300 km s^{-1} in the FU Ori spectra, were filtered from the Fourier transforms.

i) *V1515 Cyg*

Sample spectra of V1515 Cyg are shown in Figures 4 and 5. The observations are consistent with the early G supergiant spectral type suggested by Herbig (1977). The radial velocity measurements presented in Table 1 have a dispersion slightly larger than our expected measurement errors of 1.5 km s^{-1}.

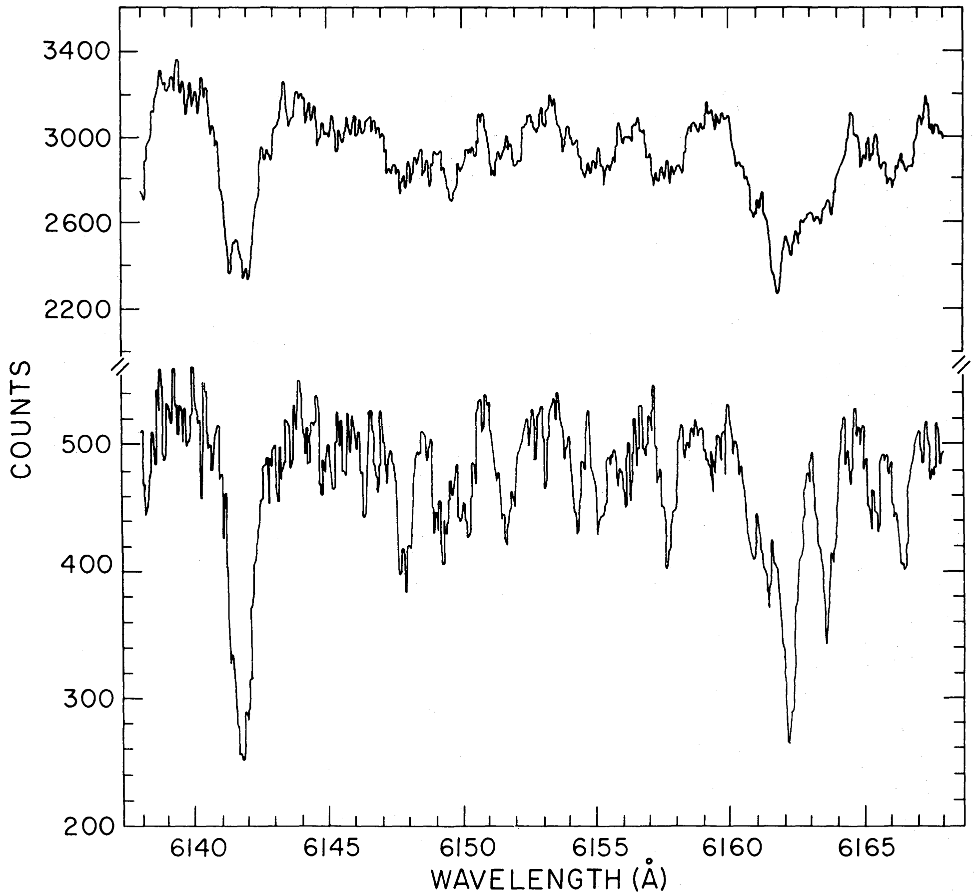

FIG. 4.—High-resolution echelle spectra of V1057 Cyg (*upper spectrum*) and V1515 Cyg (*lower spectrum*) centered at 6155 Å. The prominent Fe I λ6142 line is obviously doubled in V1057 Cyg, but not in V1515 Cyg. Other lines, including λ6158 and λ6167, also appear doubled in V1057 Cyg, as noted in the text.

Our mean heliocentric radial velocity of -14.9 ± 1.0 ($1\ \sigma$) is reasonably consistent with Herbig's (1977) value of -12 ± 2 km s^{-1}.

The widths of the cross-correlation peaks observed in V1515 Cyg are so large that the broadening of the photospheric lines must be produced by rotation or binary motion (cf. Fig. 6). We have calibrated the correlation peak widths versus $v \sin i$ as described in Stauffer *et al.* (1984). Although this method produces an estimated $v \sin i = 22 \pm 3$ km s^{-1}, we suspect that the rotational broadening function assumed is probably inappropriate (see below).

TABLE 1

RADIAL VELOCITIES OF THREE FU ORIONIS STARS

Star	$v_{\text{radial, heliocentric}}$	JD(2,440,000+)	Central Wavelength
V1057 Cyg	-12.0 ± 1.5	5603	5200
	-14.6	5983	5200
	-17.0	5983	6170
	-17.7	5984	6170
	-16.0	6012	5200
	-15.8	6013	5200
	-13.5	6015	5200
	-15.7	6036	5200
	-16.8	6037	5200
	-18.7	6038	6170
V1515 Cyg	-16.6 ± 1.5	5663	6170
	-13.7	5983	6170
	-14.7	5983	6170
	-16.5	6014	5200
	-12.6	6036	5200
FU Ori	$+25 \pm 4$	5630	5200
	$+24$	5663	5200
	$+22$	5715	5200

ii) *V1057 Cyg*

A portion of a red MMT spectrum of V1057 Cyg is shown in Figure 4. The photospheric lines have very different profiles than the corresponding features in V1515 Cyg. The unblended λ6141.73 line of Fe I (multiplet 816) is clearly double-peaked in V1057 Cyg, while no double structure is observed in V1515 Cyg, nor in several comparison stars observed subsequently. Other, weaker lines appear to be double, including the Fe I line at 6151.62 Å and the Ca I line at 6166.44 Å. Blending and the limited signal-to-noise values of our spectra complicate the search for double-peaked profiles in these weak lines.

The V1057 Cyg spectrum shown in Figure 4 is the combination of two exposures on successive nights; the cross-dispersion grating was removed and replaced between these two exposures. We have computed the cross-correlations for these two spectra separately, as shown in Figure 7. The cross-correlation of the first spectrum exhibits two peaks separated by about 30 km s^{-1}, and its shape is very similar to the profile of the 6141.7 Å line. This double structure is not seen in correlations of comparable signal-to-noise spectra of T Tauri stars rotating at similar levels (Hartmann 1985, in preparation). The cross-correlation of the second night's exposure exhibits

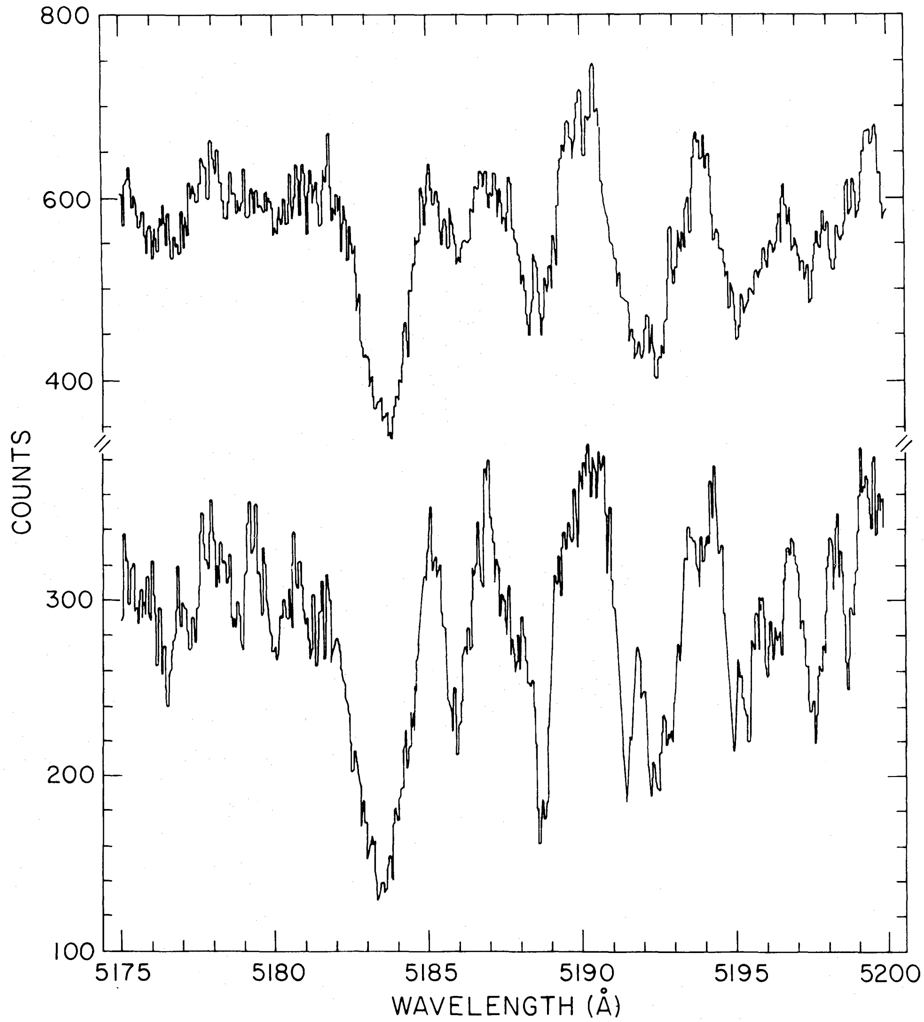

FIG. 5.—High-resolution echelle spectra of V1057 Cyg (*upper spectrum*) and V1515 Cyg (*lower spectrum*) centered at 5187 Å. A few lines that appear single in V1515 Cyg (e.g., λ5189) are doubled in V1057 Cyg, although the doubled features are not as prominent as in the red spectral region (cf. Fig. 4).

similar structure, though the red peak is weaker relative to the blue peak (Fig. 7). A third low signal-to-noise red spectrum was obtained about one month later (Fig. 8). Once again, the correlation is double-peaked, and the peaks have the same velocities observed in the previous two red spectra.

A portion of a typical blue spectrum of V1057 Cyg taken with the Whipple Observatory 1.5 m telescope is shown in Figure 5. Some of the absorption lines in V1057 Cyg appear to have double structure, especially Fe I λ5187.9. Most of the correlations of the blue spectra do not exhibit double structure, although a few show indications of peaks with the same velocity separation seen in the red correlations. The full widths at half maximum of the peaks observed in the blue and red correlations are indistinguishable within our measurement errors $\sim$5%.

The radial velocities listed in Table 1 are consistent with the values presented by Herbig (1977).

iii) *FU Ori*

Sample FU Ori spectra are displayed in Figure 9. The Mg I λ5183.62 line is displaced by -20 to -30 km s^{-1} relative to other photospheric features in FU Ori. This is a clear demonstration of the blueshifted "shell" absorption features noted in a variety of low-excitation lines by Herbig (1966). The Mg I line profile is noticeably variable, indicating substantial modulation in the mass ejection.

Before performing cross-correlations for FU Ori, we have first excised the very strong, blueshifted Mg I λ5183 line. The resulting correlation peaks in FU Ori are still generally asymmetric (Fig. 10), indicating that wind expansion affects even relatively weak photospheric lines.

Herbig and Petrov (1985) have reported that photospheric lines in the red spectral region are doubled in FU Ori. The correlation peaks produced from our blue spectra suggest that some double structure may be present, but our data are of much lower quality. The widths of the correlation peaks are consistent with the line widths reported by Herbig and Petrov.

iv) *Wavelength Dependence of Line Profiles*

The correlations of our red echelle spectra of V1057 Cyg exhibit a repeatable double-peaked structure that is not observed in the correlations of our blue spectra. Herbig and Petrov (1985) reported double structure in the red photospheric lines of FU Ori, but the profile structure is more

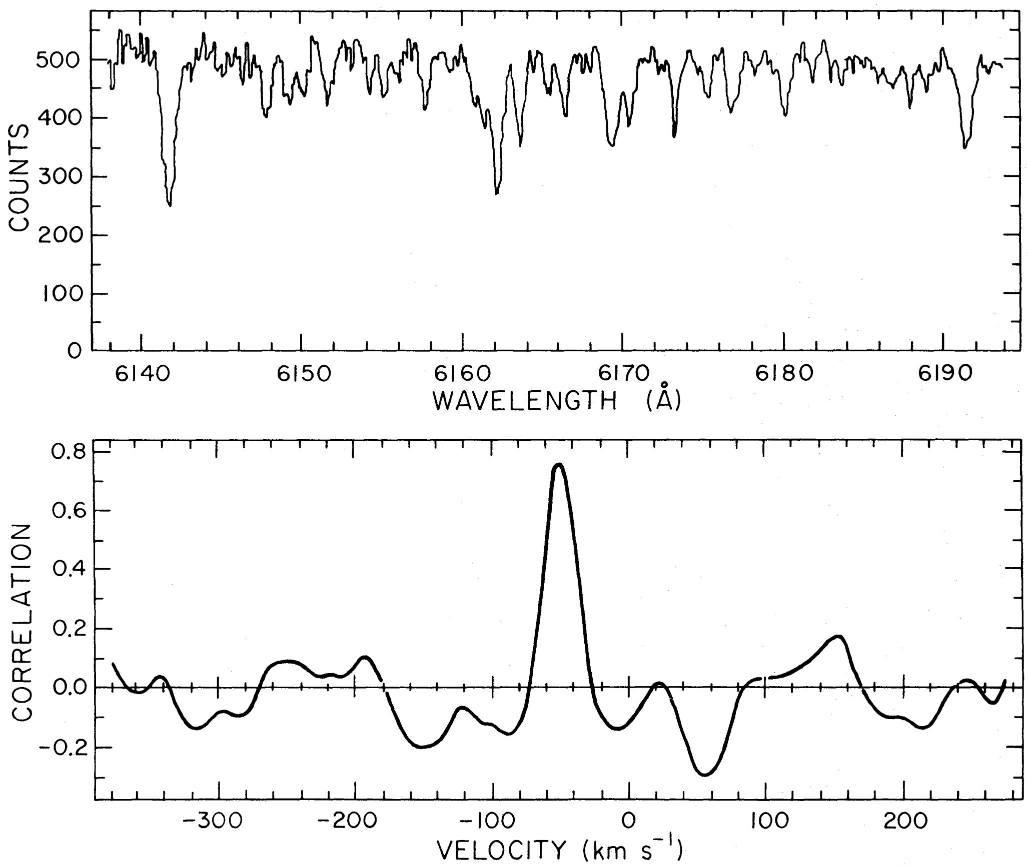

FIG. 6.—Red echelle spectrum of V1515 Cyg and its cross-correlation with the spectrum of a K-type dwarf star. This symmetric correlation peak is typical of normal single stars having a rotational velocity of 28 km s^{-1}. The velocity scales in Figs. 6, 7, 8, and 9 have an offset from heliocentric velocity due to the radial velocity of the template star.

ambiguous in the blue spectral region. The wavelength dependence of the profiles is an important fact which any interpretation of the double structure must take into account.

FU Ori, V1057 Cyg, and V1515 Cyg are known to possess strong, variable winds (Herbig 1966, 1977; Bastian and Mundt 1985). Herbig (1966) noted the presence of blue-shifted absorption components for many low-excitation lines in FU Ori. Our spectra of FU Ori show that the Mg I λ5183.62 line is clearly blueshifted by tens of kilometers per second with respect to the other photospheric lines. As described above, correlations of the blue FU Ori spectra with the Mg I line removed are usually asymmetric, indicating that the outflow begins in the upper photosphere and affects even relatively weak lines. This interpretation is strengthened by the fact that the λ5183 line arises from an excited state, so that the observed blueshifted absorption must take place in a region of high density.

Mass loss and possible turbulence associated with time variations in the wind clearly limit our ability to search for static double structure in the lines of FU Ori. As V1057 Cyg and V1515 Cyg also have powerful winds (cf. Bastian and Mundt 1985), we suspect that a similar situation is present in these objects as well.

We suggest that the difference in line profile structure between the red and blue spectral regions of V1057 Cyg is a consequence of the overall variation of photospheric absorption line strengths as a function of wavelength. In the red, photospheric lines are relatively weak and are formed deep in the photosphere, where the effects of expansion and turbulent motions should be minimal. Even with limited interference from mass loss and turbulence, the double-peaked profiles are difficult to observe in the red. We suspect that double structure is also present in the blue spectral region, but is easily obscured by variable mass loss or other turbulent motions.

Although double line structure can result from a chromospheric emission reversal, the observed wavelength dependence of the doubled profiles is the opposite of what one would expect. Chromospheric reversals should be stronger in lines formed further out in the atmosphere; observations of chromospherically active T Tauri stars indicate (as expected) that emission effects are more important at shorter wavelengths, and in the strongest absorption lines, not the weakest (cf. Strom 1983).

III. INTERPRETATION

a) Binary Model

A simple model which accounts for the doubled lines observed in FU Ori and V1057 Cyg is a binary system composed of two essentially identical G supergiants (Herbig and Petrov 1985). Assuming circular motion, the orbital period is

$$P = \frac{(M_1 + M_2)\sin^3 i}{(v \sin i/30 \text{ km s}^{-1})^3} \text{ yr} , \tag{1}$$

where M_1 and M_2 are the component masses in solar units. The observed peaks in V1057 Cyg are separated by about 30 km s^{-1}, and by about 60 km s^{-1} in FU Ori. Thus, for reason-

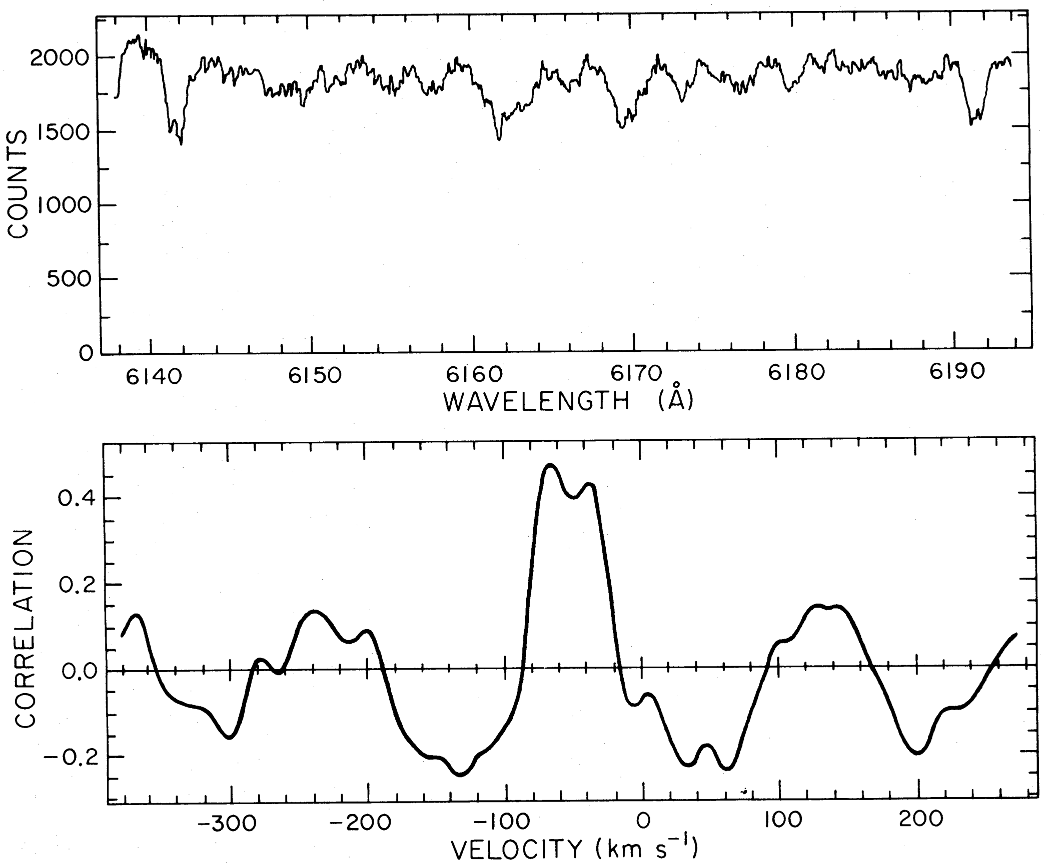

FIG. 7*a*

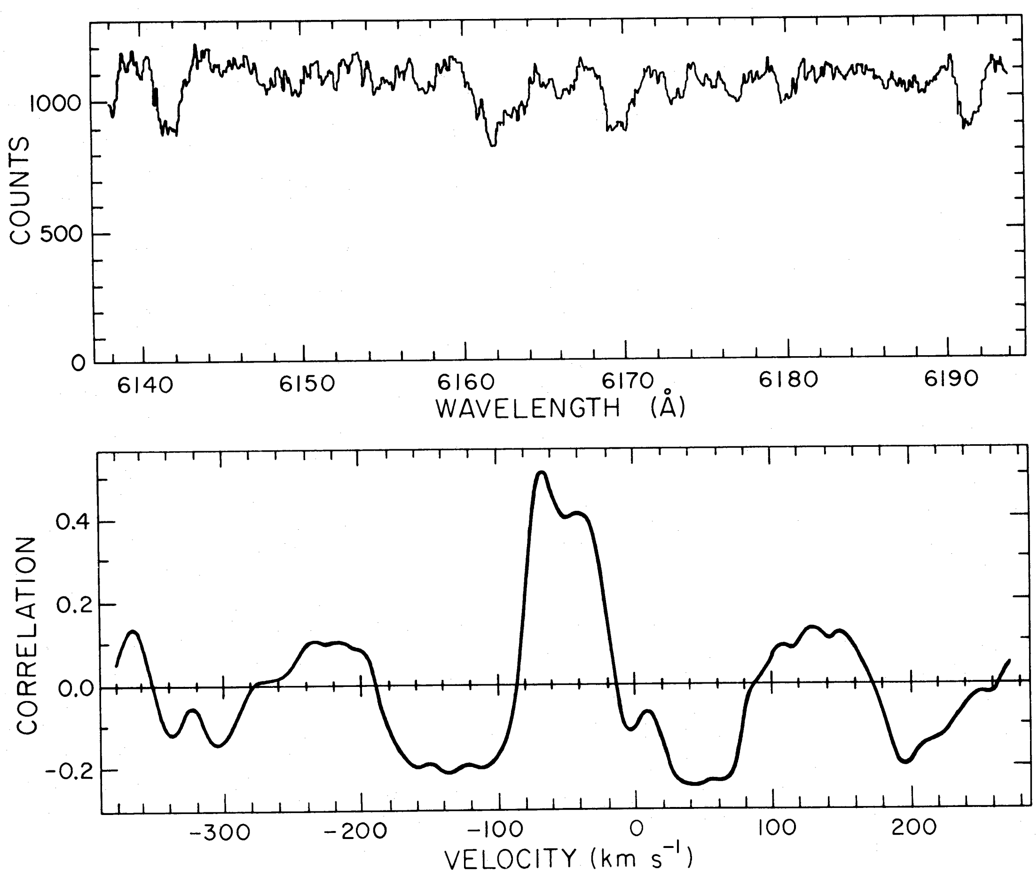

FIG. 7*b*

FIG. 7.—Red echelle spectra of V1057 Cyg—(*a*) JD 2,445,983, (*b*) 2,445,984—and their correlations with the same template star as in Fig. 6. The shape of the correlation peak represents the average absorption line profile and indicates that doubled structure is a general feature of the absorption lines in V1057 Cyg. The slight enhancement in the blue correlation peak may be a result of extra absorption in a stellar wind, as described in the main text.

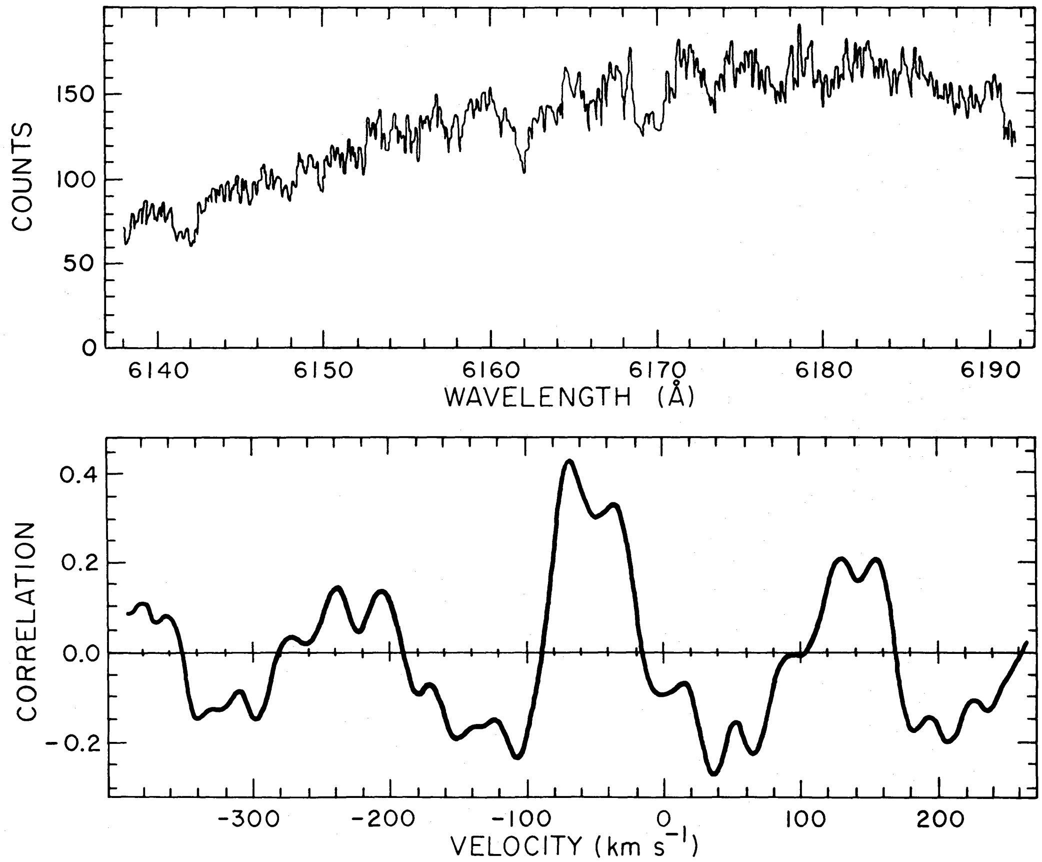

FIG. 8.—A low signal-to-noise ratio red echelle spectrum of V1057 Cyg (JD 2,446,038) and its correlation with a K-type dwarf star, as in Fig. 7

able masses the expected orbital periods of these objects are $\lesssim 1$ yr. This implies that the velocity separations of the doubled lines should change over a relatively short period of time as the stars orbit their center of mass.

Most of our spectra of V1057 Cyg were taken in the blue, where we cannot resolve the two components; however, we would expect the width of the cross-correlation peak to vary as a result of binary motion. Our nine spectra of V1057 Cyg span 1 yr, although all but one spectrum were taken over a two-month period. These data provide no evidence for variability in line widths greater than 10%. Similarly, Herbig (1984, private communication) has found no evidence for significant line width changes in FU Ori. Our blue spectra of FU Ori exhibit line width changes as measured from the correlation peaks over a range of about 25%. However, the correlation peaks are generally very asymmetric, suggesting that mass loss is significantly affecting the line profiles.

We cannot eliminate the binary model on the basis of the foregoing discussion, as the period could be close to 1 yr or the orbit could be highly eccentric. However, the binary model leaves many problems unsolved and creates some new ones:

1. The nature of the outbursts remains a mystery. Larson (1980) suggested that FU Ori outbursts result from structural readjustments of very rapidly rotating stars. One might then propose that the preoutburst star fissioned into two stars, accounting for the double line profiles, and the flattened stars would exhibit surface temperature gradients from equator to pole, producing a variation of spectral type with wavelength (cf. Mould *et al.* 1978). However, Herbig's (1977) estimate for the current optical radius of $\sim 15\ R_\odot$, coupled with a system mass close to solar, implies an orbital period $\lesssim 7$ days and orbital *and* rotational velocities $\gtrsim 100$ km s^{-1}. Such a close binary appears to be ruled out by our measurements of system line widths and the absence of detectable radial velocity variations. If the two stars are widely separated, why have they both erupted?

2. It is curious that both V1057 Cyg and FU Ori should have an M-type companion if the outbursts result from the structural readjustment of a pre–main-sequence star. Infrared observations suggest that the M-type companion has a radius of $\sim 100\ R_\odot$ and an effective temperature of ~ 2000 K, assuming distances of 500–600 pc (Mould *et al.* 1978; Herbig 1977). Since an evolved M giant is an extremely unlikely companion for a pre–main-sequence star, the proposed infrared star must be high on its Hayashi track. No equivalent luminous infrared object is known in the Taurus-Auriga cloud (Cohen and Kuhi 1979).

If the M-type star is an essential ingredient in the FU Orionis phenomenon, mass transfer from the M star might power the outbursts. We have calculated the expected orbital velocity of this system as a function of the mass ratio, assuming that the optical star has a typical T Tauri mass of $\sim 0.5\ M_\odot$ and that the M star has a radius of 100 $R_\odot$ and fills its Roche lobe. The calculated orbital velocities shown in Table 2 imply that significant velocity variations of the G star(s) should be detectable unless the mass ratio is unusually small. A direct observational test of this hypothesis can be performed; the radial velocity variation of the infrared object should be $\gtrsim 10$ km s^{-1}, considering the constraints on the optical motion.

A difficulty with this interpretation arises from the pre–

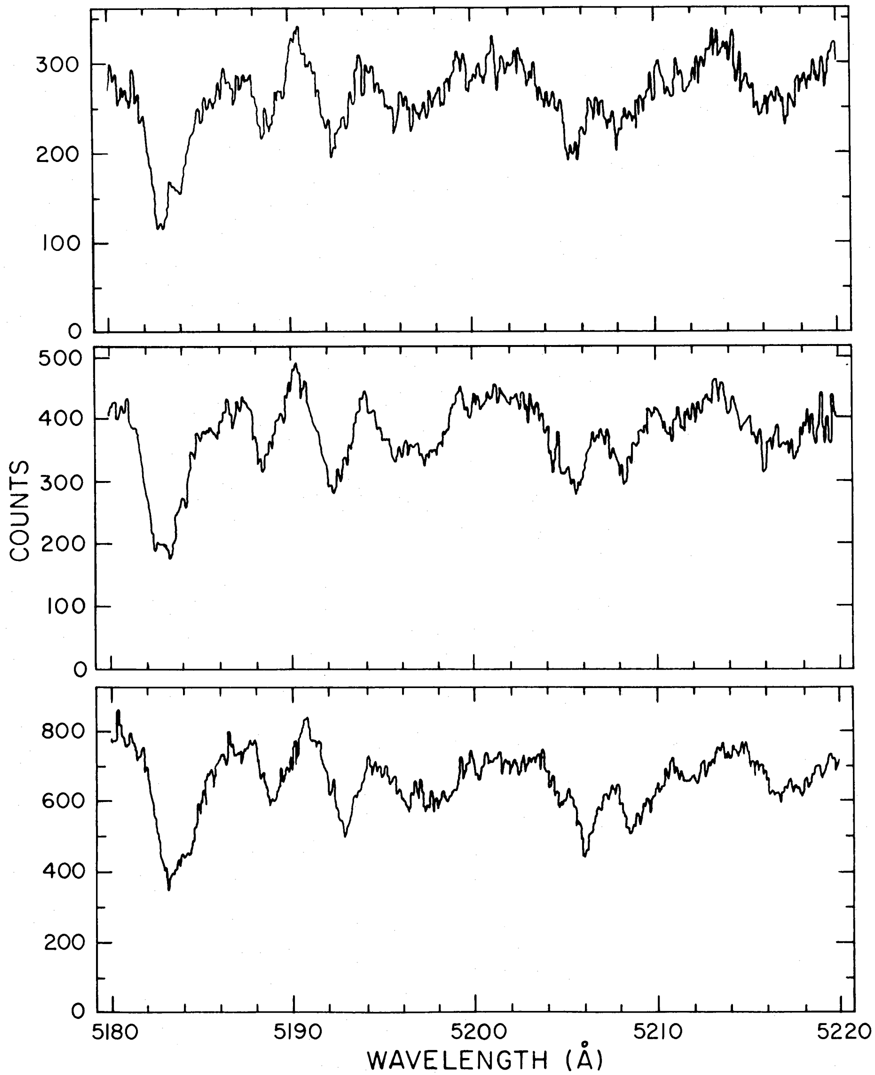

FIG. 9.—Three blue echelle spectra of FU Ori centered at 5200 Å. The Mg I λ5182 line is blueshifted with respect to other photospheric lines in FU Ori, which is an indication of mass loss.

main-sequence nature of the infrared star. If the mass of the infrared object is $\lesssim 0.5\ M_{\odot}$, its Kelvin-Helmholtz time scale is $\lesssim 10^2$ yr. It is difficult to imagine a process which would bring the stars into contact on a time scale shorter than this, in order to compensate for the contraction of the infrared star.

3. The possibility that FU Orionis outbursts are repetitive is difficult to explain with the binary model, particularly if the eruptions are due to the structural readjustment of rapidly rotating stars. With the conservative estimate that three observed events, FU Ori, V1057 Cyg, and V1515 Cyg, represent all outbursts that have occurred within 1 kpc of the Sun in the last ~80 yr, Herbig (1977) estimated that each known T Tauri star must erupt $\sim 10^2$ times in a 10^6 yr lifetime to match the observed frequency. Another estimate can be derived by assuming that any low-mass star can undergo an FU Orionis event. The average birthrate in the solar neighborhood is ~4–10 × 10^{-9} stars $pc^{-2}\ yr^{-1}$ (Miller and Scalo 1979). Thus, the number of stars born within 1 kpc of the Sun is expected to be ~4–10 × 10^{-3} yr^{-1}, implying that each low-mass star may erupt only a few times. This assumes that all recent FU Orionis events have been detected; the recent discovery of two new candidates, Elias 1-12 (Elias 1978) and the source associated with HH 57 (cf. Graham 1983; Frogel and Graham 1983; Graham and Frogel 1985) suggests that more complete searches may result in a somewhat larger frequency of FU Orionis events.

TABLE 2

PREDICTED RADIAL VELOCITIES FOR A BINARY FU ORIONIS STAR

M_2/M_1	A (AU)	P (yr)	K_1 (km s^{-1})	K_2 (km s^{-1})
1	1.2	1.3	14	14
0.4	1.5	2.2	6	14
0.1	2.2	4.4	1.4	14
0.01	4.6	14	0.1	10
0.001	9.7	43	...	7

b) *Accretion Disk Model*

The observed outburts of FU Orionis objects are reminiscent of dwarf novae, in which accretion powers the increase

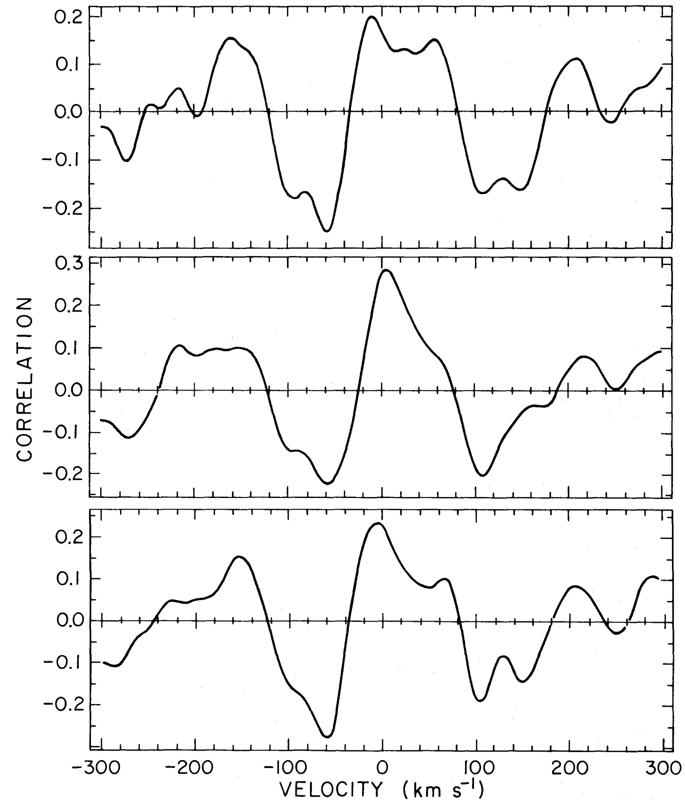

FIG. 10.—Cross-correlations of the three FU Ori spectra shown in Fig. 8 with the spectrum of a G-type dwarf star. The overall shape of this peak gives some indication of the doubled structure reported by Herbig and Petrov (1985), although the general blue asymmetry indicates that the line profiles are distorted by mass loss.

in light. We are motivated to explore an accretion disk model for FU Orionis objects by the prospect of explaining the outburst, the wavelength dependence of the spectrum, and the doubled profiles using only a single component. The radial surface temperature gradient of a large disk necessarily produces a variation of spectral type with wavelength in the required sense, and a rotating disk should exhibit double-peaked line profiles. Thus, the outbursts, the infrared and ultraviolet excesses, and the double profiles are all connected in the accretion disk model, as contrasted with the binary model. The price one pays for this economy of hypotheses is the introduction of some free parameters concealing our ignorance of viscous transport in disks. However, we now show that it is possible to make fairly detailed steady-state models for comparison with observation without depending heavily on the values assumed for the viscosity.

The standard model of accretion disks was developed by Shakura and Sunyaev (1973; cf. Lynden-Bell and Pringle 1974, and references therein). The flow of matter through the disk depends on the numerical value of the viscosity ν, of which very little is known. Shakura and Sunyaev proposed that the local viscous stress might be written as αP, where P is the local pressure and α is an arbitrary constant ≤ 1. Such "α-model" disks have become quite popular for dwarf novae and other objects, since an adequate theory of viscosity remains to be developed. Observations of dwarf novae in outburst generally confirm the predictions of the α-theory; in particular the ~ 1 week declines from optical maxima in these systems imply very turbulent disks with $\alpha \approx 0.1$–1 (Lynden-Bell and Pringle 1974; Bath and Pringle 1981; Mantle and Bath 1983; Papaloizou, Faulkner, and Lin 1983; Cannizzo 1984; Meyer and Meyer-Hoffmeister 1984; Smak 1984; and references therein). Fortunately, the appearance of a steady-state, optically thick, luminous disk is not very sensitive to the exact value of α adopted, although the time-dependent behavior of the disk, and the fundamental relationships between accretion rate and surface density within the disk, are controlled by the details of the viscosity.

i) *Constraints from Spectrophotometry*

We have constructed a model accretion disk for V1057 Cyg using a modified version of the binary synthesis program discussed by Kenyon and Webbink (1984). The disk is assumed to consist of a number of concentric annuli, each of which radiates as a star with effective temperature T_d. Assuming a steady-state, time-independent accretion disk surrounding a central star of mass M_1 and radius R_1, this temperature is given as a function of the mass accretion rate $\dot{M}$ and the radius of the annulus R as (cf. Shakura and Sunyaev 1973; Lynden-Bell and Pringle 1974):

$$T_d(R) = 26{,}890(M_1 \dot{M}/R^3)^{1/4}[1 - (R_1/R)^{1/2}]^{1/4} \text{ K}, \quad (2)$$

where M_1, R_1, and R are measured in solar units and $\dot{M}$ is measured in units of $10^{-5}\ M_\odot\ \text{yr}^{-1}$. The maximum disk temperature, which occurs at $R = 1.36R_1$, is closely related to the optical spectral type. Thus, the optical spectrum determines the ratio $M_1\dot{M}/R_1{}^3$. Estimates of the extinction and the distance to the object provide in turn an estimate for the optical radius (from the luminosity), and so determine the value of $M_1\dot{M}$.

The input optical and ultraviolet spectrophotometry has

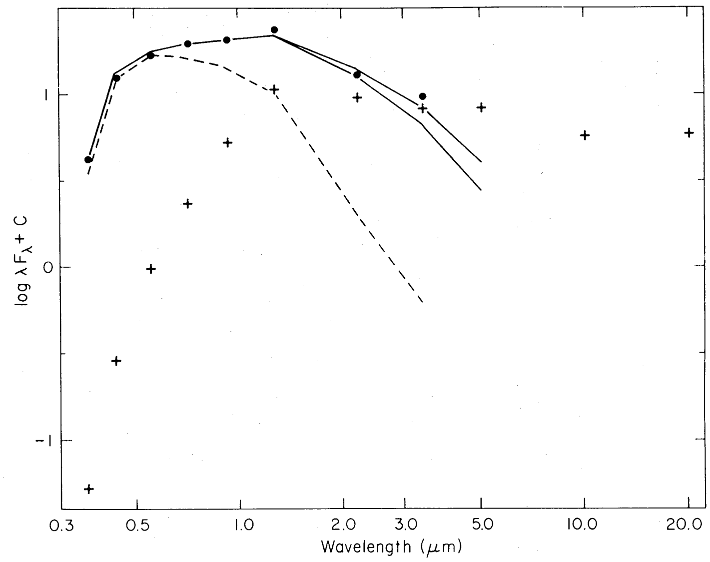

FIG. 11.—Comparison of the observed (*plusses*) and dereddened (*circles*; $E_{B-V} = 1.0$) flux distribution of V1057 Cyg with that of a G-type supergiant (*dashed line*) and two disk models with $R_2/R_1 = 50$ (*upper solid line*) and 25 (*lower solid line*).

been derived from the stellar libraries described by Jacoby, Hunter, and Christian (1984) and Wu *et al.* (1983), while infrared colors have been taken from Johnson (1966). The methods used to bin and scale these spectral data will be discussed elsewhere (Kenyon 1985). The infrared flux distribution is especially sensitive to (1) the ratio of the outer disk radius R_2 to the central star radius R_1, and (2) the emissivity of cool ($T \lesssim 2500$ K), optically thick material in the outer disk. We assume the outer disk material radiates as a blackbody with effective temperatures as given by equation (2), since the Jacoby, Hunter, and Christian (1984) spectral library does not include very low temperature objects ($T \approx 500$–2500 K). An additional uncertainty in our model is the outer radius of the disk. We have chosen $R_2/R_1 = 25$ and 50 to give the best fit to the optical-infrared colors. Larger values of R_2/R_1 increase the calculated flux at wavelengths greater than 2 μm, and so do not affect the basic conclusions discussed below.

Photometric data for V1057 Cyg obtained in 1981 (Kopatskaya 1984; Simon *et al.* 1982) are plotted in Figure 11, dereddened using a standard extinction curve (Savage and Mathis 1979). A normal G supergiant (Johnson 1966) clearly underestimates the flux at long wavelengths ($\lambda > 0.9$ μm), and Herbig (1977) showed that V1057 Cyg exhibits an excess below 4000 Å similar to that demonstrated earlier for FU Ori. A disk model with a maximum temperature of 6580 K (implying $M_1 \dot{M}/R_1^3 \approx 6.3 \times 10^{-7}$ $M_\odot^2$ yr^{-1} $R_\odot^{-3}$) reproduces the observed flux distribution of V1057 Cyg from 0.36 to 3.4 μm quite well (Fig. 11). The fit is much poorer at longer wavelengths, although the fluxes at L and M are sensitive to the choice of outer radius. The infrared fluxes beyond 5 μm are probably produced by dust emission ($T \approx 200$ K), as noted by Simon *et al.* (1982) and references therein.

The integrated V magnitude of the model disk is predicted to be (for inclination i)

$$M_V \approx 2.35 - 5 \log (R_1/R_\odot) - 2.5 \log (\cos i) , \quad (3)$$

providing $M_1 \dot{M}/R_1^3$ is held constant. Adopting a distance of 550–650 pc to V1057 Cyg implies $R_1 = 5$–6 $R_\odot$ using the 1981 dereddened visual magnitude ($V = 8.25$ for $E_{B-V} = 1.0$) and $\cos i = \frac{1}{2}$. This value for R_1 is reasonably consistent with the pre-outburst radius of 3.5–6 $R_\odot$ estimated by Herbig (1977) and results in a derived accretion rate of 1–2 $\times 10^{-4}$ $M_\odot$ yr^{-1} if the mass of the central star is 1–0.5 $M_\odot$. Similar values for $\dot{M}$ were derived for certain symbiotic stars by Kenyon and Webbink (1984).

An accretion disk provides a natural explanation for the blue excess in our FU Ori spectrophotometry, as the disk's inner edge is significantly hotter than those regions responsible for most of the visual radiation (see Table 3). An ultraviolet excess is also indicated from *IUE* spectra (Imhoff, private communication), although this result is sensitive to the adopted extinction. Our disk model predicts $m_{3100} - V$ and $m_{2600} - V$ colors of 1.8 and 2.7 respectively. These may be compared to the reddening-corrected values of $(m_{3100} - V)_0 = 1.7$ and $(m_{2600} - V)_0 > 2.4$, and represent a considerable improvement over the colors predicted for a normal G-type star ($m_{3100} - V = 2.4$ and $m_{2600} - V = 3.8$). Thus, an accretion disk reasonably accounts for the entire flux emitted by FU Ori over the range 0.26–3.5 μm.

Although the disk model reproduces the observed flux distributions of V1057 Cyg and FU Ori rather well, the inclusion of additional radiation from a hot boundary layer (produced by material coming to rest at the stellar surface) produces excess ultraviolet radiation. In the standard model, the boundary layer has a luminosity equal to that of the rest of the disk but has a very uncertain temperature distribution. The standard theory predicts boundary layer temperatures of 1–3 $\times 10^4$ K for the parameters of our disk model (Lynden-Bell and Pringle 1974; Pringle 1977); at such temperatures, the predicted boundary layer emission exceeds the flux detected shortward of 3100 Å by a factor of 2–3. Thus the simple disk model is successful in accounting for the observed energy distribution only if a fraction (perhaps $\lesssim 50\%$) of the kinetic energy at the disk's inner edge is radiated thermally.

While accretion disks and boundary layers in binary systems containing white dwarfs and neutron stars are fairly well understood, it is only recently that accretion onto normal main-sequence stars has been invoked to interpret phenomena

TABLE 3

ACCRETION DISK MODEL FOR V1057 CYGNI[a]

R/R_1 (1)	T(K) (2)	λ3520 (3)	λ5550 (4)	λ7400 (5)	λ22000 (6)
1.49	6580.	0.36	0.21	0.13	0.03
1.72	6370.	0.13	0.13	0.11	0.02
1.94	6150.	0.22	0.12	0.09	0.02
2.14	5800.	0.08	0.09	0.08	0.02
2.25	5650.	0.03	0.05	0.04	0.01
2.37	5500.	0.03	0.04	0.04	0.01
2.54	5370.	0.04	0.05	0.04	0.01
2.77	5100.	0.03	0.05	0.04	0.02
2.97	4900.	0.02	0.03	0.03	0.01
3.20	4700.	0.01	0.03	0.03	0.01
3.84	4500.	0.03	0.08	0.08	0.04
4.59	3750.	0.01	0.05	0.08	0.08
4.85	3600.	0.00	0.01	0.02	0.03
5.18	3500.	0.00	0.01	0.03	0.03
5.69	3300.	0.01	0.01	0.03	0.04
6.27	3100.	0.00	0.01	0.03	0.04
6.95	2900.	0.00	0.01	0.02	0.05
7.75	2700.	0.00	0.01	0.02	0.05
8.72	2500.	0.00	0.00	0.01	0.05
9.89	2300.	0.00	0.00	0.01	0.06
11.35	2100.	0.00	0.00	0.01	0.06
13.20	1900.	0.00	0.00	0.00	0.06
15.61	1700.	0.00	0.00	0.00	0.06
18.86	1500.	0.00	0.00	0.00	0.06
23.42	1300.	0.00	0.00	0.00	0.05
30.24	1100.	0.00	0.00	0.00	0.04
50.00	900.	0.00	0.00	0.00	0.03

[a] Columns (3)–(6) list the fractional flux emitted by a particular annulus at the indicated wavelengths.

observed in some binary stars (e.g., Kenyon and Webbink 1984). Boundary layer theories thus assume that the accreting star is a hard surface and does not react significantly to the incoming material. A star approaching or on the lower main sequence, however, possesses a substantial convective envelope which is expected to expand as a result of rapid mass inflow from an accretion disk. Indeed, detailed evolutionary calculations indicate that the photospheres of main-sequence stars ($M \approx 1$–$2\ M_\odot$) expand dramatically at high accretion rates ($\dot{M} > 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$; Webbink 1979, and references therein), robbing the boundary layer of thermal energy. The radius inferred for the central star in FU Ori is rather large for a typical low-mass, pre–main-sequence star (Cohen and Kuhi 1979), lending some support to this notion.

A second possibility is that the outer layers of the central star are rapidly rotating as a result of accretion. Material at the disk's inner edge then need not lose as much kinetic energy to come to rest on the stellar surface. This assumes that the star can spin down on a short time scale to account for the observed slow rotation of T Tauri stars (Vogel and Kuhi 1981).

ii) *Color Evolution of FU Ori and V1057 Cyg*

The outbursts of an accretion disk are presumably due to the pileup of material, followed by a change in viscosity which allows the accumulated material to be dumped onto the central star. The luminosity subsequently decreases as the disk runs out of material. If the luminosity evolution is sufficiently slow, the declining phases can be approximated by a series of steady-state disk models with decreasing mass accretion rates.

The evolution of $V-K$ and $V-L$ as a function of $B-V$ is shown in Figure 12 for model disks with $R_2/R_1 = 25$ and 50. Tick marks have been placed on the curves to indicate 1 mag decreases in the V luminosity. As the luminosity of the disk declines, its temperature drops and the colors become redder. Rapid drops in V as a function of $B-V$ are expected in late stages, as a larger fraction of the disk luminosity is radiated in the infrared. Thus, the models predict a relatively rapid decline in the optical region and a much slower decay in the infrared.

Observations summarized by Kopatskaya (1984, and references therein) and Simon *et al.* (1982, and references therein) show that V1057 Cyg has declined by ~ 2 mag in V since 1972, with smaller declines at K (~ 0.5 mag) and L (~ 0.3 mag). The brightness at 5 μm has remained roughly constant since 1972, although the brightness at 10 and 20 μm has decreased by a factor of 10 (Simon *et al.* 1982). No satisfactory explanation for the constant 5 μm flux has been developed; our fit to the 1981 photometry precludes a significant contribution from the disk unless the outer radius exceeds 400 $R_\odot$ ($R_2/R_1 \gtrsim 75$–100).

Dereddened observations of V1057 Cyg from 1972, 1974, and 1981 have also been plotted in Figure 12. It is clear that the observed trends in $V-K$ and $V-L$ as a function of $B-V$ are satisfactorily reproduced by this series of steady accretion disks. The models predict a total decline of ~ 2.5 mag in V for the observed $B-V$ variation, while V was actually observed to drop by ~ 2 mag. Given the uncertainties in approximating a clearly hydrodynamic event by a series of static models, we are satisfied that an accretion disk decaying in light as it runs out of material accounts for the color evolution of V1057 Cyg following outburst.

iii) *Line Profiles*

The disk model predicts that the line profiles will differ from those produced by rotation of a sphere. In the limit of rapid

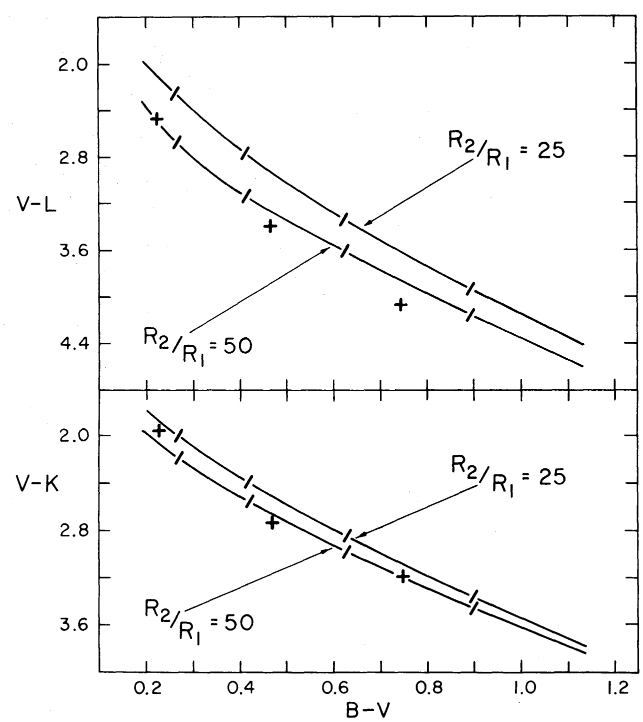

FIG. 12.—Color evolution of model accretion disks. The solid lines show the relationships between $V-K$ and $V-L$ as a function of $B-V$ for a series of steady-state accretion disk models with the indicated values of R_2/R_1. Tick marks indicate 1 mag intervals in the visual luminosity, which decreases as $B-V$ increases. Observations of V1057 Cyg during its decline (1972, 1974, 1981) have been plotted as plusses.

rotation, the profile of a line produced by a rotating thin ring or annulus is given by

$$\phi(\Delta\lambda) = [1 - (\Delta\lambda/\Delta\lambda_m)^2]^{-0.5} , \quad (4)$$

where $\Delta\lambda = \lambda - \lambda_0$ is the displacement from line center, and $\Delta\lambda_m = \lambda_0(v_{\rm rot} \sin i)/c$ is the projected rotational velocity of the annulus. While the profile produced by a single annulus is sharply double-peaked, the contributions of different annuli rotating at different Keplerian velocities smear out the peaks considerably.

We have used the detailed disk model presented in Table 3 to calculate the contribution of different parts of the disk to the profile of an arbitrary absorption line. As a first attempt, we assume that the line strength is independent of the local photospheric temperature. Measurements of the equivalent width of the λ6141.73 line in stars of differing temperatures suggest that this approximation is satisfactory as long as any contribution from the components of the disk cooler than about 4000 K is eliminated.

The predicted line profile is shown in Figure 13. It is qualitatively similar to the observed λ6141.73 profile and to the cross-correlation peaks for V1057 Cyg. Scaling the line profile width to the larger rotational velocity of FU Ori produces a result similar to that described by Herbig and Petrov (1985), who characterized the double line profiles as consistent with two identical G stars rotating at 35 km s^{-1}, separated by 60 km s^{-1} in radial velocity. We note that observation of double-peaked profiles in the more slowly rotating object V1515 Cyg should be very difficult with 10 km s^{-1} resolution and the signal-to-noise values of our spectra.

An important prediction of the disk model is that the apparent rotational velocity should vary with wavelength, since different parts of the disk will dominate different spectral regions. From our disk model, we estimate that the rotational velocity of FU Ori at 6300 Å should be about 10% less than that observed at 4500 Å. This change is probably below practical detection limits. However, the rotational broadening at 2 μm should be about half the broadening observed in the optical spectral region. FTS observations of the 2 μm water feature (e.g., Mould *et al.* 1978) may be able to test this hypothesis.

iv) *Rotational Velocities*

Herbig (1977) suggested that the progenitors of FU Orionis objects are low-mass, pre-main-sequence stars, based in part on a pre-outburst spectrum of V1057 Cyg. This suggestion appears to be consistent with the disk models discussed in the previous section. Assuming $M_1 \approx 0.5\ M_\odot$ and an optical radius $R_{\rm opt} \approx 14\ R_\odot$ (cf. Herbig 1977), the optical $\langle v \sin i \rangle$ for our model disk is 65 km s^{-1} for $\langle \sin i \rangle = \pi/4$. Our estimates of optical rotation for V1515 Cyg, V1057 Cyg, and FU Ori are 22, 45, and 75 km s^{-1} respectively, for a mean rotation of 47 km s^{-1}. One may expect an observational bias against observing a disk at inclinations approaching 90°, produced by the heavy extinction associated with the disk.

IV. A MODEL FOR OUTBURSTS

The total mass accreted in an FU Orionis outburst is fairly large. For a central star mass of $\sim 0.5\ M_\odot$, an accretion rate of $\sim 10^{-4}\ M_\odot$ yr^{-1} is required to account for the eruption of V1057 Cyg. The total accreted mass is then $\sim 10^{-2}\ M_\odot$, assuming the current rate of decline continues until V returns to its pre-outburst level ($\sim$ 100 yr). If the star undergoes several outbursts, as suggested by event statistics, then a reservoir of mass approaching 0.1 $M_\odot$ is required. We now consider possible sources of this material and the physics underlying the rapid accretion phase.

a) *Binary Star Model*

The most natural source for the material needed to power an outburst is a Roche lobe–filling companion to the accreting star. However, the presumed size of the disk ($R \gtrsim$ 1–2 AU) requires a wide binary separation ($A \gtrsim 5$ AU) and a very long orbital period ($P \gtrsim 10$ yr). Only a very low-mass object ($M \lesssim 0.01\ M_\odot$) can potentially fill its tidal lobe at these separations

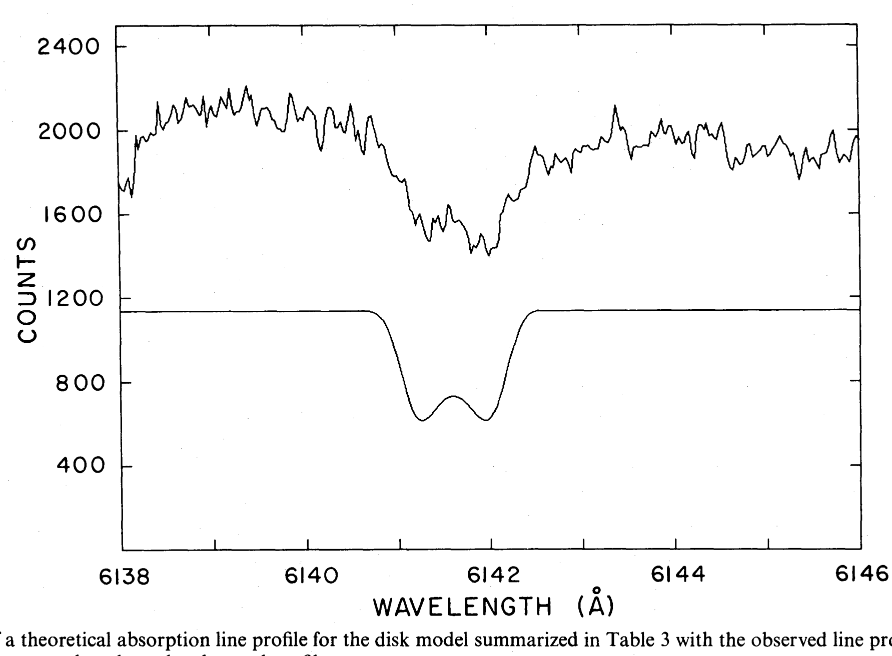

FIG. 13.—Comparison of a theoretical absorption line profile for the disk model summarized in Table 3 with the observed line profile of the λ6173 line in V1057 Cyg. Numerical values for counts apply only to the observed profile.

(Table 2); such a "star" is unlikely to be responsible for repeating accretion events given the constraints on the mass accreted in an FU Orionis outburst.

b) *Protostellar Nebula Model*

Another possible source for the accreted material is a remnant protostellar nebula, as it is plausible that a disk of the required mass or greater is left over after gravitational collapse of the central object. We suggest, as proposed by Lin (1985), that instabilities in this nebula result in outbursts similar to those observed in FU Ori and V1057 Cyg. If a disk instability does occur, repeated outbursts fueled by continued inflow of material from the remnant nebula are a distinct possibility and may be required by the event statistics. Herbig (1977) has suggested that the repeated flares of stars like VY Tau may be related to the FU Orionis phenomenon, and relatively small scale instabilities may explain this behavior as well.

We envision that a "pre-fuor" is a newly formed T Tauri star surrounded by a modest disk-shaped nebula that is nearly identical in structure to the primordial solar nebula discussed by Lin (1981; $R \approx 10^{14}$ cm, $M \approx 0.01\ M_\odot$, $T_d \approx 300$–1000 K). The opacity in this disk is dominated by dust grains, and infall from a surrounding cloud injects material *into* the disk at a rate given by $\dot{M}_n$. We assume that the mass flow rate *through* the disk ($\dot{M}_d = 3\pi\nu\Sigma$, where ν is the viscosity and Σ is the surface density) is initially smaller than $\dot{M}_n$. The disk then attempts to increase its mass and effective temperature until $\dot{M}_d = \dot{M}_n$. If the thermal structure of the disk [i.e., $\nu(T_d)$ or $\Sigma(T_d)$] remains essentially unchanged by this evolution, the disk can achieve an equilibrium state with a minimum amount of effort. However, if $\nu(T_d)$ or $\Sigma(T_d)$ should increase dramatically as a consequence of the increased disk mass, the resulting evolution of $\dot{M}_d$ could produce an optical outburst.

The analysis of such "disk instabilities" has become very popular in recent years, once it was realized that this mechanism might result in dwarf nova eruptions (e.g., Osaki 1974; Faulkner, Lin, and Papaloizou 1983, hereafter FLP; Cannizzo and Wheeler 1984, hereafter CW; Meyer and Meyer-Hofmeister 1982, hereafter MMH; Mineshige and Osaki 1983, 1985; Smak 1984). While the physics of disks is not understood in detail (Pringle 1981), it is currently believed that the quiescent ("cold") state of a dwarf nova is characterized by $T_d \approx 6000$ K and $L \approx 0.1\ L_\odot$. Sudden changes in the optical depth brought about by (1) variations in the opacity as a function of surface density, or (2) the onset of convection cause dramatic changes in the viscosity α and the surface density Σ, resulting in optical outbursts. Recent hydrodynamic calculations suggest that rapid transitions ($\sim$1–2 days) from the cold state to the hot state can produce light curves which closely resemble those observed in short-period dwarf nova systems (Cannizzo 1984; Faulkner, Lin, and Papaloizou 1983; Meyer and Meyer-Hofmeister 1984; Smak 1984).

Although hydrodynamic calculations have not been published for the conditions we suspect occur in the disks surrounding FU Orionis stars, we can make some estimates of the conditions at the point of instability. Since dust grains provide the dominant opacity source in the cold disk ($T_d \approx 1000$ K), the surface density is approximately (Lin 1981)

$$\Sigma \approx 60\alpha^{-1/2}(R/200\ R_\odot)^{3/4}(T_d/1000\ \mathrm{K})^{1/2}\ \mathrm{g\ cm^{-2}}\ . \quad (5)$$

We anticipate that the thermal structure of this disk changes dramatically when T_d exceeds 1500–2000 K and the grains begin to melt. The disappearance of the major opacity source (FLP) and the onset of convection (CW; MMH) may lead to rapid increases in the effective temperature (T_d) and the viscosity, and therefore the dramatic evolution in Σ which we observe as an optical eruption. The mass flow rate through the disk at the onset of the instability is $3\pi\nu\Sigma$; substituting equation (5) for Σ and $\alpha c_s H$ for ν, where c_s is the sound speed and H is the scale height of the disk ($\sim 0.1R$), this becomes $\dot{M}_d \approx 2 \times 10^{-6}\alpha^{1/2}(R/200\ R_\odot)^{9/4}\ M_\odot\ \mathrm{yr}^{-1}$, when T_d is $\sim$2000 K. The mass stored in the disk at this point is $\delta M_d = \int 2\pi r\Sigma dr \approx 2 \times 10^{-5}\alpha^{-1/2}(R/200\ R_\odot)^{11/4}\ M_\odot$. Adopting $R \approx 200\ R_\odot$ from our best-fit disk model leads to $\alpha \approx 10^{-4}$ for a stored mass of $0.01\ M_\odot$. This results in a quiescent mass flow rate through the disk of $\sim 2 \times 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$, or a storage time of $\sim 5 \times 10^5$ yr. The important point to note is that a relatively small viscosity is adequate to store the required amount of mass on a reasonable time scale. Considering the uncertainties in the estimate of R_d and the strong functional dependence of $\dot{M}_d$ and δM_d on R_d, it is reassuring that the storage time can be comparable to or slightly less than the lifetime of a typical T Tauri star (about a few times 10^6 yr). It is therefore possible to have more than one outburst per star, as suggested by event statistics.

The cold state of the disk described above produces a disk luminosity of $\lesssim 0.1\ L_\odot$, most of which is radiated at temperatures below 1000 K. Such infrared radiation is compatible with observations of many T Tauri stars (see Cohen 1975, and references therein) and would be difficult to distinguish from dust reradiation of absorbed stellar photons.

These simple calculations suggest a low state with $\alpha \approx 10^{-4}$, which can be compared with the $\alpha \approx 0.05$ derived for the cold states of dwarf novae (Smak 1984). The low state of FU Orionis stars (1000 K) is significantly colder than that typical of dwarf novae (6000 K), and thus a smaller α does not seem unreasonable, especially if magnetic viscosity is important in dwarf novae (MMH). Magnetic effects are likely to be small in the cold state of FU Orionis objects, if most of the disk material is not convective.

An important constraint of any model for FU Orionis eruptions is the rise time from the quiescent state to visual maximum, Δt. The two important time scales in an evolving disk are the thermal diffusion time scale, $\Delta t(\mathrm{thermal}) \approx (R_d/H)/\alpha\Omega$, and the viscous time scale, $\Delta t(\mathrm{viscous}) \approx (R_d/H)^2/\alpha\Omega$, where R_d is a characteristic disk radius, H is the local disk scale height, and Ω is the angular velocity. Assuming $\alpha \approx 1$ and $R_d/H \approx 0.1$, $\Delta t(\mathrm{thermal}) \approx 1.6 R_d^{3/2} M_1^{1/2}$ yr, and $\Delta t(\mathrm{viscous}) \approx 16 R_d^{3/2} M_1^{1/2}$ yr, where R_d is measured in AU and M_1 is the disk mass in $M_\odot$. The transition from the cold state to the hot state described above is expected to develop on a thermal time scale, while the transfer of matter through the disk occurs on a viscous time scale. Thus Δt(thermal) should approximate the rise time of an eruption in an extended accretion disk, with Δt(viscous) the typical duration of the decline from visual maximum. If accretion should be confined to a torus at a large radius from the central star, matter must be (1) heated to the high state and (2) allowed to flow towards the central star. The viscous time scale should control the rise and decline from light in these objects.

If we adopt $M_1 \approx 0.5\ M_\odot$ and $R_d \approx 1$ AU from our disk model, $\Delta t(\mathrm{thermal}) \approx 1.1$ yr and $\Delta t(\mathrm{viscous}) \approx 11$ yr. The $\sim$400 day rise times of FU Ori and V1057 Cyg are thus consistent with a disk instability in an extended disk, and the 2.5 mag decline of V1057 Cyg in the past 15 yr is close to that expected of a disk losing material on the viscous time scale. The decline of FU Ori ($\gtrsim$50 yr) is significantly longer than anticipated;

given the uncertainties in the disk radius discussed above, the lack of an optical decay is not yet an embarrassment to the basic theory [for $R_d \approx 5$ AU, Δt(viscous) ≈ 125 yr].

V1515 Cyg has risen on a much longer time scale. This slow rise could be the evolution of a viscous disk, and the eruption of this object might be the result of a thermal instability in a torus.

V. MASS LOSS AND BIPOLAR FLOWS

The evidence for powerful winds from FU Orionis stars (Herbig 1966, 1977; Bastian and Mundt 1985) is interesting in view of the evidence for massive flows from young stars, with some indication that the ejection is bipolar (Snell, Loren, and Plambeck 1980; Snell and Edwards 1981; Bally and Lada 1983; Schwartz 1983, and references therein). Several authors have studied the interaction of stellar winds with a surrounding anisotropic interstellar medium, attempting to produce bipolar flows from an initially isotropic stellar wind (see Canto and Rodriguez 1980; Königl 1982).

We suggest that the winds of FU Orionis stars arise from the surface of the disk, which is much more luminous in outburst than the central star, and has a lower surface gravity. A disk wind should naturally produce a bipolar flow, regardless of the mechanism of mass loss, without requiring collimation by the surrounding interstellar medium. Preliminary calculations (Croswell, Hartmann, and Avrett 1985, in preparation) indicate that the small quantity of redshifted emission in the Hα profiles of these stars (see Bastian and Mundt 1985) imply substantial occultation of receding material, in agreement with the disk picture. These calculations suggest that the mass loss rate from FU Ori may be as much as $\sim 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$, enough to have an appreciable impact on the surrounding gas.

Bastian and Mundt (1985) suggested that the mechanism driving T Tauri winds probably also applies to the FU Orionis stars. Alfvén waves have been suggested as the most plausible mechanism for T Tauri stars by DeCampli (1981) and Hartmann, Edwards, and Avrett (1982). Since our model disk is convective, it is quite possible that large magnetic fields are generated (see MMH). If energy fluxes and magnetic fields similar to those invoked for T Tauri stars can be generated, waves could be especially effective in driving a disk wind, since the effective gravity at the disk surface is smaller than for a typical pre-main-sequence star.

It seems unlikely that accretion at the rates required to power FU Orionis outbursts can occur for periods $\gtrsim 10^4$ yr (implying the accretion of more than $\sim 1\ M_\odot$). Such outbursts may dominate the dynamics of the neighboring medium on short time scales, while the steady mass loss observed from T Tauri stars may dominate the momentum transfer to the interstellar medium on time scales of 10^6 yr (see Franco 1984).

VI. CONCLUSIONS

We have shown that an accretion disk model naturally accounts for the observed variation of spectral type with wavelength in FU Orionis stars, as well as the doubled line profiles observed in FU Ori by Herbig and Petrov (1985) and in V1057 Cyg by us. The absence of binary motion suggests that an instability in the nebula left over from the formation of the central star gives rise to the outbursts of these objects, and we estimate that $\lesssim 10^{-2}\ M_\odot$ is accreted by the central pre-main-sequence star during the event. The observed winds, ejected from the surface of a disk, can produce massive bipolar flows.

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