HIGH-RESOLUTION SPECTROSCOPY OF FU ORIONIS STARS

G. H. HERBIG
Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822

P. P. PETROV
Crimean Astrophysical Observatory, p/o Nauchny, Crimea 98409, Ukraine

AND

R. DUERMULLER
Astronomy Division, University of Oulu, P.O. Box 3000, Oulu FIN-90014, Finland

Received 2003 February 28; accepted 2003 May 29

ABSTRACT

High-resolution spectroscopy was obtained of the FU Orionis stars FU Ori and V1057 Cyg between 1995 and 2002 with the SOFIN spectrograph at the Nordic Optical Telescope and with HIRES at Keck I. During these years FU Ori remained about 1 mag (in B) below its 1938–39 maximum brightness, but V1057 Cyg (B ≈ 10.5 at peak in 1970–1971) faded from about 13.5 to 14.9 and then recovered slightly. Their photospheric spectra resemble that of a rotationally broadened, slightly veiled supergiant of about type G0 Ib, with $v_{\text{eq}} \sin i = 70 \text{ km s}^{-1}$ for FU Ori, and 55 km s$^{-1}$ for V1057 Cyg. As V1057 Cyg faded, P Cyg structure in H$\alpha$ and the IR Ca ii lines strengthened and a complex shortward-displaced shell spectrum of low-excitation lines of the neutral metals (including Li i and Rb i) increased in strength, disappeared in 1999, and reappeared in 2001. Several SOFIN runs extended over a number of successive nights so that a search for rapid and cyclic changes in the spectra was possible. These spectra show rapid night-to-night changes in the wind structure of FU Ori at H$\alpha$, including clear evidence of sporadic infall. The equivalent width of the P Cyg absorption varied cyclically with a period of 14.8 days, with phase stability maintained over three seasons. This is believed to be the rotation period of FU Ori. The internal structure of its photospheric lines also varies cyclically, but with a period of 3.54 days. A similar variation may be present in V1057 Cyg, but the data are much noisier and that result uncertain. As V1057 Cyg has faded and the continuum level fallen, the emission lines of a pre-existing low-excitation chromosphere have emerged. Therefore we believe that the “line doubling” in V1057 Cyg is produced by these central emission cores in the absorption lines, not by orbital motion in an inclined Keplerian disk. No convincing dependence of $v_{\text{eq}} \sin i$ on wavelength or excitation potential was detected in either FU Ori or V1057 Cyg, again contrary to expectation for a self-luminous accretion disk. It was found also that certain critical lines in the near infrared are not accounted for by synthetic disk spectra. It is concluded that a rapidly rotating star near the edge of stability, as proposed by Larson, can better account for these observations. The possibility is also considered that FUor eruptions are not a property of ordinary T Tauri stars but may be confined to a special subspecies of rapidly rotating pre-main-sequence stars having powerful quasi-permanent winds.

Subject headings: stars: evolution — stars: individual (FU Orionis, V1057 Cygni) — stars: pre-main-sequence — stars: variables: other

1. INTRODUCTION

The variable star now known as FU Ori was originally believed to be a slow nova because of its leisurely rise from $m_B = 16$ to 10 over an interval of about a year in 1937–1939. There were some misgivings at the time about that classification: the spectrum was quite unlike that of an ordinary nova, and for a nova the star was most unusually located in the dark cloud Barnard 35, itself in the OB association surrounding λ Ori. It is now realized that FU Ori is no nova but represents another phenomenon altogether. It is the prototype of a small class of pre-main-sequence objects, named “FUors” by Ambartsumian, that have received an increasing amount of attention over the past three decades.

Three additional stars, and possibly two more, now collectively define the FUor class on the grounds of a well-documented major rise in brightness, association with a molecular cloud, and a spectrum like that of FU Ori. These “classical FUors” are V1057 Cyg, V1515 Cyg, V1735 Cyg, probably V346 Nor (Reipurth 1990), and possibly a star (CB 34V = V1184 Tau) discussed most recently by Alves et al. (1997). A number of other pre-main-sequence stars have been proposed for membership, usually on the grounds of spectroscopic resemblance plus an infrared excess, but none have been observed to brighten up and remain so for years, as did the classical FUors mentioned above.

The time seems appropriate for a reexamination of the observational situation for two reasons. First, the other classical FUors remain not far from their maximum brightness, but V1057 Cyg has faded about 4 mag (in B) since 1971.

Second, high-resolution spectroscopy has now become feasible for all FUors over a wider wavelength range (3500–9000 Å) than was heretofore possible, and in the case of V1057 Cyg almost on an annual basis. The observations to be discussed here have been obtained by Petrov and...
collaborators with the SOFIN echelle spectrograph (Tuominen, Ilyin, & Petrov 1990) of the Nordic Optical Telescope at La Palma between 1996 and 2002 at a resolution of about 13 km s$^{-1}$ and by Herbig with the HIRES echelle at the Keck I Telescope on Mauna Kea since 1996 at a resolution of about 7 km s$^{-1}$. Several of the SOFIN runs extended over a number of successive nights, offering the opportunity to search for rapid changes in the spectra. Some of the SOFIN material has already been discussed by Petrov et al. (1998) and by Laakkonen (2000). We here expand upon those results.

It is now accepted that FUors represent an interesting phenomenon of early stellar evolution, but it is uncertain how universal it is, and there is disagreement on what is responsible for the outbursts. Hypotheses as to the latter fall into two classes: Hartmann, Kenyon, and their colleagues have proposed that the flare-up is a phenomenon not of the preoutburst star itself but the result of a major increase in the surface brightness of the circumstellar accretion disk. Since the idea was first put forward by Hartmann & Kenyon (1985, hereafter HK), it has been elaborated extensively (and reviewed: Hartmann & Kenyon 1996). Building upon that proposition, theories of instabilities intrinsic to such an accretion disk have been examined by Clarke, Lin, & Pringle (1990), Kley & Lin (1999), and Bell (1999, which includes references to earlier papers).

The opposite hypothesis is that the star itself is responsible for the FUor flare-up. The absorption lines in the classical FUors are broad; if they are the result of axial rotation in a spherical limb-darkened star, fits to the optical-region line profiles ($\xi$) yield values of $v$ sin $i$ up to about 70 km s$^{-1}$ in the case of FU Ori. A periodic modulation of the line structure of FU Ori (described in §4.4) leads to a radius of the order of 20 sin $i$ $R_\odot$. Given those parameters, the condition at which FU Ori would be rotationally stable (in the sense that the centrifugal acceleration at the equator of an oblate rotator equals the gravitational [Porter 1996]) is $(M/M_\odot)$ sin $i > 0.79$. Clearly, a not unreasonable value of sin $i$ would require a substantial stellar mass to ensure the stability of such a rapid rotator.

An examination by Larson (1980) of the consequences of such very rapid rotation suggested that barlike deformations would develop that could produce heating of the outer layers of the star, thus accounting for the flare-up and mass loss. One would think that such instabilities might produce detectable photometric variation with the rotation period. The only search for such variations is that reported for FU Ori by Kenyon et al. (2000). They found only "random" fluctuations of amplitude 3%–4% on timescales of 1 day or less, but it would be worthwhile to repeat such observations with better time coverage. Later (§4.4) we describe the results of a search for cyclic variations in radial velocity and line structure in both FU Ori and V1057 Cyg.

Little more has been heard of the rapid-rotator hypothesis, perhaps because of the appeal of the disk-instability idea and the volume of publication that it has engendered. But on earlier occasions we have pointed out some difficulties and our reservations about the HK proposal (Herbig 1989; Petrov & Herbig 1992). The theory was subsequently modified to explain one of those concerns (Bell et al. 1995). However, the new results to be described here call into question the original observational justification for the HK hypothesis, on which that theory is based. In the following sections we examine three issues that have been regarded as crucial support for that hypothesis:

1. The "doubling" of certain absorption lines is evidence of Keplerian motion in an inclined disk (§2.4).
2. A dependence on $v$ sin $i$ on wavelength or excitation potential in the optical region up to 9000 Å is evidence of the decline in orbital velocity with radius expected under the disk hypothesis (§4.2).
3. The theoretical disk spectrum, as a composite of annuli of temperature and surface brightness that decline with distance from the center, fits the observed spectra of FUors (§4.1).

When V1057 Cyg was bright, it was noticed that the spectral type became later with increasing wavelength across the optical region. The effect became striking when observations were extended to the near-IR (Mould et al. 1978; Elias 1978) and $H_2O$ and CO bands were found in the spectrum of an ostensibly F- or G-type star. No evidence of radial velocity variation with time or with wavelength has been reported, so the spectrum apparently originates in a single object. The disk hypothesis does have the persuasive advantage of explaining, although not in detail (§4.1), this apparently composite nature of FUor spectra as the falloff of temperature with increasing radius in an accretion disk.

But it is now realized that the simple presence of the 2.3 μm CO bands in a G supergiant is not that unusual (Wallace & Hinkle 1997). They appear at about G0 Ib and are prominent by G8 Ib, although in FU Ori and V1057 Cyg they are as strong as in early M-type stars. It would be interesting to investigate whether such an effect could be simulated in an extended envelope around a rapidly rotating single star.

We are not necessarily committed to the concept of an unstable rapid rotator as a final solution to the FUor phenomenon. But for lack of a more persuasive alternative, in what follows we examine the observational information in terms of that hypothesis. First we describe the spectrum of V1057 Cyg during its 1996–2002 fading, the period for which we have detailed high-resolution coverage (§2); this is followed by a discussion of its light curve (§3), and then we review the spectroscopic properties of FUors in general (§4).

2. THE SPECTRUM OF V1057 Cyg 1996–2002

Figure 1 shows the B/pg light curve of V1057 Cyg. Most of the high-resolution spectra of V1057 Cyg discussed in the literature were obtained in the 1980s, when the star was descending to a plateau of brightness about between $B = 13.0$ and 13.3, which extended from 1985 to about 1994. Between 1994 and 1995 it began to fade again, reaching a minimum near 14.9 in 1999, since which it has...
recovered slightly. Briefly, following Petrov et al. (1998) and Laakkonen (2000), this is what happened in the spectrum during the post-1994 minimum with respect to the 1980s:

1. The photospheric lines became much shallower, some with pronounced emission cores; the P Cyg absorptions in Hα, infrared Ca ii, and other lines became stronger.

2. The shortward-shifted shell components in the low-excitation lines increased in strength (1996–1997), then essentially disappeared (1999), but reappeared in 2001.

3. TiO bands in the expanding shell appeared for the first time, and a number of emission lines of low excitation appeared in the spectrum.

2.1. Photospheric Spectrum

Simple inspection of the absorption spectrum of V1057 Cyg shows that it resembles that of a rotationally broadened early-G supergiant. To make this quantitative, the excitation temperature and gravity were determined as follows. Equivalent widths (EW) were measured for 30 of the least blended photospheric lines of Fe i in the region 4950–8000 Å (shell components, which could distort the measurements, were almost absent in this spectral region in 1998–1999). The curve of growth gives \( T_{\text{exc}} = 5300 \pm 300 \) K. The single measurable line of Fe ii, \( \lambda 5991 \), lies on this curve at a position corresponding to \( \log n_e = 12 \). These are indeed values expected for a G1 supergiant. Furthermore, a comparison of V1057 Cyg with templates of 41 Cyg (F5 II), \( \beta \) Aqr (G0 Ib), 9 Peg (G5 Ib), and 40 Peg (G8 II) show that the line ratios correspond to F7–G3 I–II.

The photospheric absorption lines in 1997 August appeared to be shallower than in the spectra found in the literature. Many of the lower excitation lines appear double as the result of what is clearly an emission component at the bottom of the absorption. With respect to spectra of the 1980s, this line "doubling," measured as a velocity separation between the two absorption minima, had increased by 1996 October, and even more by 1997 August, as the result of what is clearly an emission component appearing at the bottom of the absorption line (see \( \S \) 2.4). However, the line width of the absorptions near the continuum level remains the same as in the spectra taken, e.g., in 1983–1984 by Kenyon, Hartmann, & Hewett (1988) and in 1992 by Hartmann & Calvet (1995). That is, the overall line width has not changed, but in those where the central reversal has become more prominent the line depth has been reduced. In this way many photospheric lines appear significantly shallower than in the accretion disk model of Kenyon et al. (1988), which was designed to fit the spectrum of V1057 Cyg in 1985 (Fig. 13).

However, there is another effect as well: in the red, higher excitation lines where no central emission is expected are also shallower than in the spun-up standards, as if a veiling continuum is superposed upon the absorption spectrum. Veiling factors of 0.3–0.5 are indicated.

2.2. Wind/P Cyg Features

Table 1 gives the parameters of the P Cyg structure at Hα as measured on all spectra either published or our own. One sees that the mass-loss in the wind of V1057 Cyg, as evidenced by the strength of the P Cyg absorption component at Hα, began to increase about 1984–1985 (Laakkonen 2000), near the beginning of the photometric plateau. It is tempting to speculate that the two may be connected. Earlier, the P Cyg absorption of Hα was not saturated, and its structure varied considerably at all velocities (Croswell, Hartmann, & Avrett 1987; Table 1). During the postplateau minimum (i.e., after 1994–95) the line remained strong, but the high-velocity wing (−200 to −400 km s\(^{-1}\)) varied in depth from year to year while the low-velocity section (−60 to −120 km s\(^{-1}\)) always remained deep (Figs. 7 and 24).

The only known observations of Hα during the plateau decade are those obtained in 1988 by Welty et al. (1992) and by K. Budge (unpublished). Those entries in Table 1 have been measured from their profiles. The EW of the P Cyg absorption component in that year was the largest that has been reported. No other observations of Hα are known to have been made during 1986–1995, but Rustamov (2001) measured the structure of Hβ and Hγ between 1978 and 1990 (photographically and at a resolution of about 1000). His data indicate that the EW of Hβ declined from 1978 to 1985 but had increased again by 1987 (no observation in 1986), continued to increase thereafter, and by 1990 was the largest he had observed.

The lack of adequate spectroscopic coverage of V1057 Cyg during the 1986–1995 decade is regrettable.

Figure 2 shows the P Cyg profiles of the Hα, Hβ, Na i, and Ca ii λ8542 lines on the 1997 August SOFIN spectrum. (Throughout we denote the measured [heliocentric] velocity of a features as \( \overline{v} \) and the stellar velocity as \( v_* \), so
velocity in the star’s rest frame is $RV = v - v_\odot$). The Hα profile is similar to that of FU Ori, where the mass-loss rate was estimated to be an order of magnitude larger than in V1057 Cyg in 1985 (Crosowell et al. 1987).

### 2.3. Shell Features

The low-excitation (<1 eV) photospheric absorption lines of V1057 Cyg have almost always been flanked shortward by narrow, often complex “shell” features. They are prominent in the strong low-excitation lines of the neutral metals at shorter wavelengths. They are probably due to condensations in the expanding wind passing in front of the star. In 1996, by which time the star had faded by about 1 mag (in $B$) from plateau brightness, both the P Cyg absorption at the Balmer lines and the shell lines had become stronger, to such a degree that the shell also became detectable at many lines in the red.

Figure 3 shows some shell line profiles at the 13 km s$^{-1}$ SOFIN resolution. The underlying photospheric spectrum has been subtracted, as described later (§ 2.5). The strong lines of higher excitation potential (EP), such as Mg i λ5183 and Fe ii λ5316, also contain shortward shell components but at more negative velocities, about $-120$ km s$^{-1}$. These absorptions are much broader than those at the low-excitation lines and so represent an intermediate case between shell and wind.

Another indicator of a cool expanding shell are the numerous TiO bands (Fig. 4). All the TiO bands were blueshifted to $RV = -40$ to $-70$ km s$^{-1}$, i.e., to about the same velocity as the shell components of low-excitation lines. These shell lines and the TiO bands in the red were strongest in 1996, weaker in 1997, and absent in 1998, 1999, and 2000. By 2001 the shell lines and TiO bands had reappeared, but with somewhat broader profiles and larger expansion velocities (see Fig. 4).

The complexity of the shell structure is more apparent at HIRES resolution, where at least five separate components are seen. The shell was so prominent in 1996–1997 at low-level lines of neutral metals (Al i, Fe i, Ti i, Cr i, and Mn i), as well as in Ba ii, Li i, and Rb i, as to confuse the shortward wings of the underlying stellar features. The 4990–5020 Å region, containing a number of prominent Ti i lines, is shown in Figure 5. At the top of the figure is the same section in the G5 Ib star HD 190113, as broadened by $v_{eq} \sin i = 55$ km s$^{-1}$, to represent the underlying photospheric spectrum.

At that time (1997 August 12–13), the shell lines were at velocities of $-128$, $-107$, $-89$, $-78$, and $-61$ km s$^{-1}$; the velocity of the star itself is near $-16$ km s$^{-1}$. A number of these complex shell lines have been decomposed in the following way. Each component was represented as a pure absorption line of depth $e^{-\tau}$, where $\tau$ was a Gaussian (of the form $\exp[-0.5(\delta i/\sigma)^2]$) whose velocity, depth, and FWHM could be adjusted; the observed profile followed by adding the individual values of $\tau$ at every pixel across the line. Figure 6 shows fits to Ti i λ4999, where dashed lines outline the individual components, the solid line outlines the observed profile, and a series of crosses show the representation. Table 2 gives the parameters found to fit
two representative Ti i lines as well as Ba ii/C21 6496, Li i/C21 6707, and Rb i/C21/C21 7800, 7947.

A source of uncertainty in these fits was the choice of continuum level under the shell line. Ideally that would be the underlying photospheric line spectrum as represented by an artificially broadened F–G supergiant (as in Fig. 5), but it

Fig. 2.—P Cyg structure of the Hα (upper left), Hβ (upper right), Na i D1,2 (lower left), and Ca ii λ8542 (lower right) lines in V1057 Cyg from the SOFIN spectra of 1997 August.

Fig. 3.—V1057 Cyg shell lines in 1997, from SOFIN spectra of 13 km s\(^{-1}\) resolution. The spectrum of β Aqr, spun up to 55 km s\(^{-1}\) and veiled by a factor of 0.3, has been subtracted. The velocity scale is in the stellar rest frame. Low-excitation lines (EP < 1 eV) are shown by solid lines, and higher excitation lines (2–3 eV) are dashed. The strong lines of higher excitation potential, such as Mg i λ5183 and Fe ii λ5316, have as well shortward-shifted components at large velocities, about −120 km s\(^{-1}\).

Fig. 4.—Shell TiO bands in the spectrum of V1057 Cyg in 1996, 1997, and 2001. The photospheric spectrum has been subtracted. The strong absorption near 6706 is the Li i shell component. The lowermost curve is the spectrum of 72 Leo (M3 IIIb).
was clear that an adequate match could be achieved only by adding in a veiling continuum as well. Until this effect could be understood and applied in a consistent wavelength-dependent fashion, it was decided simply to interpolate the continuum level linearly between two points just outside either edge of the shell line. The equivalent widths of components 1 and 2 are particularly susceptible to errors in the continuum level so defined. Nine unblended Ti\textsc{i} lines having lower levels between 0.0 and 1.4 eV were synthesized in this way. For each of the five shell components, the EWs were fitted to a theoretical pure-absorption curve of growth, and the values of the parameter $\tau_0$ (the Doppler width in velocity units), the excitation temperature $T_{\text{exc}}$, and the total Ti\textsc{i} column density $N$(Ti\textsc{i}) were extracted. They are listed in Table 3. These temperatures are estimated to be uncertain by several hundred degrees. For most components $\tau_0$ ranges between about 2 and 5 km s$^{-1}$.

**TABLE 2**

| Shell Line Structure in V1057 Cyg |
|-------------------------------|
| Number | $v$ (km s$^{-1}$) | $\tau_0$ (km s$^{-1}$) | $\sigma$ (km s$^{-1}$) | EW (mA˚) |
|-------|-----------------|---------------------|-----------------|--------|
| Ti\textsc{i} 4997.099 (RMT 5) |
| 1      | -               | -                   | -               | -      |
| 2      | -107.0          | 0.022               | 5.4             | 5.1    |
| 3      | -90.0           | 0.26                | 3.6             | 36.0   |
| 4      | -78.0           | 0.33                | 4.5             | 56.1   |
| 5      | -59.5           | 0.27                | 4.8             | 49.1   |
| Ti\textsc{i} 4999.504 (RMT 38) |
| 1      | -128.0          | 0.08                | 3.9             | 13.0   |
| 2      | -107.5          | 0.27                | 5.1             | 53.0   |
| 3      | -88.5           | 0.87                | 6.0             | 165.0  |
| 4      | -78.0           | 1.17                | 6.0             | 202.0  |
| 5      | -61.5           | 1.77                | 5.1             | 221.0  |
| Ba\textsc{ii} 6496.896 (RMT 2) |
| 1      | -128.0          | 0.23                | 8.3             | 96.0   |
| 2      | -107.0          | 0.27                | 6.5             | 86.0   |
| 3      | -92.5           | 0.33                | 5.5             | 89.0   |
| 4      | -80.0           | 0.82                | 7.8             | 267.0  |
| 5      | -61.0           | 1.00                | 6.5             | 265.0  |
| Li\textsc{i} 6707.81 (RMT 1) |
| 1      | -128.0          | 0.17                | 8.0             | 72.0   |
| 2      | -104.0          | 0.31                | 8.7             | 136.0  |
| 3      | -82.0           | 0.96                | 8.3             | 326.0  |
| 4      | -60.5           | 1.29                | 8.0             | 389.0  |
| Rb\textsc{i} 7800.227 (RMT 1) |
| 1      | -129.0          | 0.075               | 6.9             | 33.0   |
| 2      | -106.0          | 0.085               | 7.7             | 41.0   |
| 3      | -79.5           | 0.32                | 10.0            | 194.0  |
| 4      | -58.5           | 0.52                | 4.6             | 131.0  |
| Rb\textsc{i} A7947.69 (RMT 1) |
| 1      | -126.0          | 0.078               | 4.9             | 25.0   |
| 2      | -100.0          | 0.065               | 4.9             | 21.0   |
| 3      | -81.0           | 0.21                | 9.8             | 127.0  |
| 4      | -60.0           | 0.32                | 5.3             | 101.0  |

Note.—The symbols are as follows: $v$ is the central (heliocentric) velocity of that component, $\tau_0$ is its central optical thickness, and $\sigma$ is its width, both expressed as Gaussian parameters as explained in the text, and EW is its equivalent width.
rubidium, is detectable only as \( \text{Ba}^{\text{II}} \). One would expect it to be ionized because barium, with first ionization potential (IP) of 4.8 eV, so the nondetection of \( \text{Cs}^{\text{II}} \) is intermediate between the thermal velocities for Ti (1.1 km s\(^{-1}\)) and H (8 km s\(^{-1}\)) at the values of \( T_{\text{exc}} \) of Table 3. However, the measured FWHMs of the individual Ti\( \text{I} \) shell lines scatter between about 8 and 19 km s\(^{-1}\) (following allowance for the instrumental FWHM of 6 km s\(^{-1}\)). This shows that there is another source of line broadening in these expanding shells, possibly weak unresolved structure.

Eight unblended Fe\( \text{I} \) shell lines were analyzed in the same way. The scatter in the fit of the Gaussian EWs to the curve of growth was much larger than for Ti\( \text{I} \), possibly because of greater uncertainties in defining the continuum level. Only the results for the \(-78\) and \(-61\) km s\(^{-1}\) components are considered reliable. The \( T_{\text{exc}} \) for Fe\( \text{I} \) was very clearly lower than for Ti\( \text{I} \), between about 1350 and 1500 K. The total column density if \( T_{\text{exc}} = 1500 \) K is near \( \log N(\text{Fe}\text{I}) \) = 17.4. This difference between the values of \( T_{\text{exc}} \) of Ti\( \text{I} \) and Fe\( \text{I} \) is puzzling, because their identical velocity structures indicate that they originate in the same parcels of rising gas. Possibly non-LTE conditions in the shell are responsible.

The evolution of the shell and wind absorptions during the brightness minimum of 1996–2001 is shown in Figure 7, from SOFIN spectra. One might expect that the shell features would be stronger at minimum brightness, but in fact at minimum in 1998–1999 it was the wind features that were enhanced, while the shell components were strongest in 1996–1997 and 2001. This is illustrated in Figure 8, which compares the 4660–4690 Å region on the HIRES spectrogram of 1997 August 12 (below) with that of 1998 October 30 (above). The Ti\( \text{I} \) shell lines (4667.58 and 4681.91) were strong on the first date but had essentially disappeared 15 months later. At that second date, weak, narrow emission lines (arrow) at approximately the stellar velocity were detectable.

An unusual feature of the shell spectrum is the prominence of the lines of Rb\( \text{I} \) at 7800 and 7947 Å. Their EWs in the \(-78\) km s\(^{-1}\) component were 194 and 127 mA\( \text{˚} \) in 1997 August. The first ionization potential (IP) of Rb is 4.8 eV, so one would expect it to be ionized because barium, with first IP = 5.2 eV and a comparable meteoritic abundance to rubidium, is detectable only as Ba\( \text{II} \) (46496, EW = 267 mA\( \text{˚} \)). The nondetection of Cs\( \text{I} \) \( \lambda 8521 \) is understandable because of the still lower first IP of cesium (3.9 eV) and a lower meteoritic abundance (Rb/Cs = 19), but the strength of Rb\( \text{I} \) remains unexplained.

| Component (km s\(^{-1}\)) | \( \zeta_0 \) (km s\(^{-1}\)) | \( T_{\text{exc}} \) (K) | \( \log N(\text{Ti}) \) (cm\(^{-2}\)) |
|--------------------------|-----------------|-----------------|-----------------|
| \(-128\)                  | 1.3             | 4000            | 13.38           |
| \(-107\)                  | 1.9             | 4350            | 14.08           |
| \(-89\)                   | 3.1             | 3650            | 14.78           |
| \(-78\)                   | 4.7             | 3600            | 15.05           |
| \(-61\)                   | 4.8             | 3700            | 14.95           |

2.4. The Emission Lines

Before 1997 the only obvious optical emission lines in V1057 Cyg were the components of the P Cyg structure of H\( \alpha \) and Ca\( \Pi \). In that year, when the star had begun its decline following the 1985–1994 plateau, a number of emission lines of low excitation appeared in the centers of the corresponding stellar absorptions (Petrov et al. 1998). The most conspicuous were Fe\( \text{I} \) \( \lambda 8047 \) and \( \lambda 8074 \) (Revised Multiplet Table [RMT] 12), followed by Fe\( \text{I} \) \( \lambda 8514 \), Fe\( \text{II} \) \( \lambda 6516 \), Ca\( \Pi \) \( \lambda 6572 \), and Fe\( \text{I} \) \( \lambda 7912 \) (RMT 60, 40, 1, and 12, respectively; see Fig. 9). These emission peaks are at about the stellar velocity and are narrower than the photospheric absorption lines. A higher resolution HIRES spectrogram of 1997 August 13 confirms the asymmetry of the \( \lambda \lambda 8047, 8074 \) lines that is apparent in Figure 9: their shortward edges are clearly steeper than the longward. Most of these same low-excitation emission lines were observed long ago in the G supergiant \( \rho \) Cas by Sargent (1961).

This appearance of emission in the centers of many low-excitation absorption lines is illustrated in Figure 10, which compares the 6400 Å region on a Lick coude spectrogram of 1985 May 27 (resolution about 18 km s\(^{-1}\)) with the HIRES spectrogram of 1997 August 13, slightly smoothed. In those intervening 12 yr, the centers of the Fe\( \text{I} \) absorption lines \( \lambda \lambda 6393, 6400 \) increased in brightness with respect to the continuum, rising at peak to almost the continuum level. (A second Lick spectrogram obtained on 1985 September 25 showed that no change had taken place during those 4 months.)
We believe that this emission spectrum is produced in a warm layer, which we call a "chromosphere," that is almost overwhelmed by the photospheric continuum when the star is bright, except through its marginal appearance as emission cores in lower excitation stellar absorption lines. However, that chromosphere must have become brighter by a factor of about 2 between 1985 and 1997. The reason is that between those dates V1057 Cyg faded by only about 0.9 mag in \( V \), so if the 1997 emission cores in \( \lambda \lambda 6393, 6400 \) had been present at that same absolute brightness in 1985, they would have filled those absorption lines up to about half the depth actually observed.

To determine whether there was any further change in the brightness level of the chromosphere, the EWs of several emission cores were measured in the SOFIN differential spectra (§ 2.5) of V1057 Cyg (minus \( \beta \) Aqr spun up to km s\(^{-1} \) and not veiled) between 1996 and 2001. The results are given in Table 4. Over these years, the emission-line EWs remained constant within the errors of measurement; i.e., as the star faded, the lines became weaker in the same proportion. We conclude that there was no further change in the absolute intensity of the chromosphere after the increase by a factor of approximately 2 sometime between 1985 and 1997.

This brightening of the chromosphere may have been related to the increase in the wind activity that began in 1984–1985 (§ 2.2).

As V1057 Cyg has declined in brightness, the fading of the continuum has helped to reveal this chromospheric emission spectrum. We believe that it is this spectrum that is responsible for the apparent "doubling" of some absorption lines.
that has been suggested as evidence of orbital motion in a Keplerian disk. In an earlier paper on the spectrum of FU Ori (Petrov & Herbig 1992) we argued for such an explanation of the “doubling,” a possibility in fact first mentioned by Goodrich (1987). The fading of V1057 Cyg has now provided strong support for that interpretation.

These central reversals that have emerged as distinct emission lines since 1995 are not very strong, e.g., Fe i $\lambda$8047 has a peak intensity of only 5%–8% above the continuum level. If the continuum were 1 mag brighter (or the chromosphere fainter), the line would appear only as an emission fringe at H $\alpha$.

The strong Ca ii H and K emission lines at 3933 and 3968 $\AA$ (discussed in § 4.6) and at the infrared triplet are probably produced in this chromosphere, presumably the same that D’Angelo et al. (2002a, 2002b) found necessary to reproduce the H $\alpha$ profile of FU Ori. The Balmer emission lines that ought to be produced in the same region are concealed by the P Cyg structure of the wind, except for the longward emission fringe at H $\alpha$.

The shortward edges of the Ca ii emission lines are truncated by their own P Cyg absorptions. Clearly, the outflowing wind is located above this chromosphere, demonstrated also by the presence of fluorescent Fe i $\lambda$4063 and $\lambda$4132 lines in V1057 Cyg: those Fe i atoms “see” the exciting Ca ii $\lambda$3968 emission line, although it is hidden from us by the wind component of H $\alpha$.

A very broad emission, at peak only about 0.12 above continuum level, is present at 6297 $\AA$ on the HIRES spectrum of 1997 August 13 (that region falls between orders on other exposures). It must be [O i] $\lambda$6300.30 because the weaker [O i] line at 6363 $\AA$ is present on other HIRES and SOFIN spectra of 1996–1998. The central velocity of $\lambda$6300 is about $-135$ km s$^{-1}$, its total width at continuum level about 180 km s$^{-1}$. A similar broad, shortward-displaced emission line is also present at the position of [Fe ii] $\lambda$7155. They have nearly the same velocity as the “intermediate case between shell and wind” components mentioned in § 2.3. No such features are found in FU Ori.

The reader should be aware that FUors are not unique in possessing broad absorption lines with emission cores and CO absorption in the 2 $\mu$m region: a number of normal (i.e., not pre–main-sequence) F- and G-type high-luminosity stars are known to have such spectra. Several examples were mentioned by Petrov & Herbig (1992), and more recently the classical case of $\rho$ Cas has been rediscussed by Lobel et al. (2003).

To summarize, in addition to the photospheric spectrum, these sets of spectral features were present in V1057 Cyg during this period at different radial velocities:

1. Wind at $-100$ to $-300$ km s$^{-1}$ (H $\alpha$, D$_{12}$ Na i, Ca ii, Mg i, Fe ii).
2. Shell at $-40$ to $-110$ km s$^{-1}$ (TiO and low-excitation atomic lines in absorption).
3. CO molecules at about the stellar velocity (§ 4.3).
4. Low-excitation chromospheric emission at the stellar velocity.

![Fig. 10.—6385–6408 $\AA$ region in V1057 Cyg, from a Lick CCD spectrogram of 1985 May 27 (dotted line) and a HIRES spectrogram of 1997 August 13 (solid line); the latter has been smoothed by a 3 pixel box. In the intervening 12 yr the centers of the 6393, 6400 $\AA$ Fe i absorptions have become emission lines, with peak intensities nearly at continuum level.](image-url)
2.5. The Differential Spectrum

As already pointed out, a number of low-excitation lines clearly went into emission above the continuum during the brightness minimum of 1996–2001. It is natural that the same feature should be present in higher excitation lines, if only as an emission core at the bottom of the absorption line but enough to cause those lines to appear double and shallow, as is observed (Petrov & Herbig 1992; Petrov et al. 1998). Such line emission can be revealed by subtracting the underlying photospheric spectrum. As a template for the photospheric spectrum of V1057 Cyg we use $\beta$ Aqr spun up to $v_{\text{eq}} \sin i = 55$ km s$^{-1}$ and veiled by 0.3. Two fragments of this differential spectrum are shown in Figure 11 for the average spectrum of 1998–2000. Note that the relative strength of the emission lines is not the same as in the absorption spectrum.

Both the “true” emissions (that rise above the continuum) and those revealed in such a differential spectrum fall along a common curve of growth for $T_{\text{exc}} = 3600 \pm 300$ K, $\log n_e = 7.5 \pm 0.5$. This temperature is significantly lower than photospheric. In the M-type dwarf VY Tau, the same emission lines appeared very strong by contrast with that low-temperature continuum (Herbig 1990). There is a good correlation between the equivalent widths of the low-temperature line emissions in VY Tau and those in the differential spectrum of V1057 Cyg (Fig. 12). Note that the relative strength of the emission lines is not the same as in the absorption spectrum.

Although the observed line intensities can be explained as a sum of the photospheric and emission-line spectra, the observed line profile is not just a sum of two Gaussians. Weaker lines have a rather “boxy” shape, with sharp edges, while stronger lines (without shell components) have nearly normal rotational profiles except for the emission cores. This difference suggests some abnormality in the structure of the lower atmosphere, deserving of attention at high resolution $\geq 60,000$ and $S/N \geq 300$.

3. V1057 Cyg: INTERPRETATION OF THE LIGHT CURVE

The conventional assumption is that a FUor outburst represents only a temporary event and that the star will eventually return to its former brightness. The slow fading of FU Ori over the past 60 yr, and the relatively rapid decline of V1057 Cyg since about 1971 might be explained in this way. But the spectrum of V1057 Cyg does not

![Fig. 11. Two sections of the differential spectrum (solid line) obtained as a difference between that of V1057 Cyg (dashed line) and the template spectrum of $\beta$ Aqr, spun up to 55 km s$^{-1}$ and veiled by 0.3.](image1)

![Fig. 12. Correlation between equivalent widths of emission lines in V1057 Cyg and VY Tau. Filled circles: The “true” emission lines seen above the continuum level in V1057 Cyg. Open circles: The emission lines revealed in the differential spectrum of V1057 Cyg.](image2)

![Fig. 13. Photospheric lines in the average spectrum of V1057 Cyg in 1998–2000 (thick solid line). Shown for comparison are the spectrum of $\beta$ Aqr, spun up to $v_{\text{eq}} = 55$ km s$^{-1}$ and veiled by 0.3 (thin solid line), and the synthetic spectrum of the accretion disk (dashed line), calculated according to Kenyon et al. (1988).](image3)
support this expectation. Before the 1970 outburst, the star possessed Hα emission that, in order to have been detected at all in the first low-resolution surveys, by Haro (1971) in the early 1950s and by Herbig (1958) in 1952–1956, must have had an equivalent width of approximately 25–40 Å. No such emission has appeared at Hα during the decline to the 1999–2000 minimum: the emission fringe has remained near EW(Hα) = 1–2 Å (Table 1).

Another departure from expectation is the following. Before the outburst a number of Fe i and Fe ii emission lines were reported (Herbig 1958), so they must have been fairly strong to have been detectable on that 1957 low-dispersion photographic spectrogram. Yet at the present time no Fe ii emission lines are detectable in the blue-violet on modern, far superior digital spectrograms, although the fluorescent Fe i λ4063 and λ4132 lines are weakly present.

Furthermore, as the star has declined one would have expected the absorption spectrum to approach that of a T Tauri star–like K- or M-type dwarf. In 1998–1999 V1057 Cyg was only about 1.5 mag (in B) above its preoutburst level (B = 14.9), so if the star was returning to its original T Tauri state, a late-type photosphere and emission-line spectrum ought to have emerged. But in spite of the drop in brightness, the spectral type of V1057 Cyg remained the same as in the 1980s: in § 2.1 it was shown that the star continues to resemble a rapidly rotating G supergiant, unlike any other pre–main-sequence star of which we are aware. But the spectroscopic similarity is deceptive: the values of MV are quite different. If the surface brightness and (V−R)J color of V1057 Cyg at the time of the 1985–1994 plateau were the same as those of the standard G0 Ib β Aqr, then correction for A_V = 2.35 mag leads to M_V = +0.3 for a distance of 600 pc. This compares with M_V = −3.5 for β Aqr. That value of M_V for V1057 Cyg would be produced by a single star of uniform surface brightness having a radius of about 9 R_☉.

Given these considerations and the fact that V1057 Cyg both pre- and postoutburst was unusual in its possession of a very massive high-velocity wind (§ 4.6), we later speculate that preoutburst FUors are not normal T Tauri stars (TTSs) but represent a special subspecies of that class.

We suggest that the behavior of V1057 Cyg as it has faded, as well as the general spectroscopic properties of the classical FUors, may be understood in terms of a stratified atmosphere atop a rapid rotator with a strong quasi-permanent outflowing wind, a low effective g being responsible for the line-spectrum resemblance. The emission spectrum which has appeared as the continuum of V1057 Cyg has faded is, as we have stressed, that of a low-excitation chromosphere atop the stellar atmosphere (§ 2.4).

The decline of V1057 Cyg from its 1971 peak brightness to the plateau level in 1985–1994 can be represented by a continuous change in radius and surface brightness of a rapid rotator, those quantities being derivable from the procedure of Barnes, Evans, & Parsons (1976) and the above values of extinction and distance. Observed V and (V−R)J for 1971–2001 were taken from Kopatskaya et al. (2002), for 1978–2001 from Ibrahimov (1996, 1999, and private communication [2002]), and for 1971 from Mendoza (1971) and Rieke, Lee, & Coyne (1972). The resulting values of R_/R_☉ are plotted in Figure 14. The symbols identifying the

sources of the photometry are explained in the caption. Radial and surface brightnesses depend upon whose colors are used. If the Ibrahimov data, Figure 14 shows how R_/R_☉ fell from about 14 near maximum light to about 9 at the time of the plateau. The surface brightnesses declined from values appropriate a late A-type main-sequence star in 1971 to a mid-K type in 1995.

We emphasize that such calculations do not prove that the source is a spherical star, only that the brightness and color can be represented by a circular surface of those dimensions and surface brightness.

In 1984–1985 the wind flux began to increase (§ 2.2), and at about the same time the decline in brightness halted. Sometime between 1985 and 1997—we speculate that it may have been early in that interval—the chromosphere is known to have brightened with respect to the continuum. Thus all three phenomena may have been consequences of an upsurge of activity in the underlying rapidly rotating star.

The plateau episode ended when, between 1994 and 1995, the star abruptly became fainter by 0.78 mag in B, and redder by 0.18 mag in B−V (seasonal averages; see the small plot of B−V vs. time at the bottom of Fig. 1). The ratio ΔB/Δ(B−V) = 4.3 is not far from the standard interstellar

7 Kopatskaya (1984) also used the Barnes et al. (1976) formulation to calculate R_/R_☉, but from its dependence on B−V. Our radii come instead from the dependence on (V−R)J, following the recommendation of Barnes et al., and the fact that an excess shortward of 4800 Å was present between 1971 and 1975–1976 (Herbig 1977, Fig. 8), which would make B−V suspect. It is of course unclear which color is more likely to be applicable to an unusual object like V1057 Cyg.
reddening value (4.1). Thereafter (§ 2.4) the continuum and chromosphere fluctuated in brightness together, so we ascribe the 1994–1995 fading to screening by a dust layer somewhere higher in the atmosphere. This is not a new idea: the possibility of dust condensation in the outflowing wind of V1057 Cyg has already been raised by Kolotilov & Kenyon (1997), and it will be recalled that Kenyon et al. (1991) interpreted a relatively brief dimming of the FUor V1515 Cyg in 1980 as such an event. The formation of such a dust layer was also envisioned by Kameswara Rao et al. (1999) in the case of R CrB, also a high-luminosity G star.

However, V1057 Cyg continued to fade, \( \Delta V = 0.63 \text{ mag} \) by 1999, apparently without any further change in color. Either more dust dominated by large particles or a continuation of the slow post-1971 decline could be responsible.

The foregoing is an attempt to pull together the photometric and spectroscopic phenomena exhibited by V1057 Cyg since the 1970–1971 outburst. However, it is likely that the atmospheric structure is not radially homogeneous, as this picture may seem to imply. The day-to-day and secular fluctuations observed in the H\( _\alpha \) structure at both V1057 Cyg and FU Ori show that wind ejection is spasmodic, possibly coming from localized areas on the rotating star, rather as the fast solar wind emerges from “coronal holes” likely coming from localized areas on the rotating star, Cyg and FU Ori show that wind ejection is spasmodic, possibly coming from localized areas on the rotating star, rather as the fast solar wind emerges from “coronal holes” on the Sun. It would then not be surprising if the wind fields above these stars contained much structure. The Hubble Space Telescope (HST) images of V1057 Cyg (§ 3.1) show that the distribution of dust near that star, whether formed in and ejected by the star or local dust shaped by the stellar wind, is highly structured.

The disappearance and reappearance of the shell spectrum of V1057 Cyg on a timescale of a few years cannot be due to pure radial expansion and the consequent decline in column density proportional to \( r^{-2} \). It may be caused by the movement of inhomogeneities in the wind structure across the line of sight. The broad shortward-shifted [O i] and [Fe ii] lines described in § 2.4 could then arise in this expanding, inhomogeneous envelope, their longward wings being occulted by the star.

Unexplained is the veiling mentioned earlier that was used to account for the general shallowing of the absorption spectrum. It is conceivable that the line shallowness is intrinsic, i.e., the result of integration over a very nonuniform stellar hemisphere, or of line formation in a highly nonspherical extended atmosphere, or of the contribution of a continuum originating in the chromosphere. If extrinsic, thermal emission by dust is an unlikely explanation, because although the energy absorbed in the hypothetical dust layer must reappear somewhere, dust would not survive at temperatures greater than about 1500 K, so reemission would be significant only at long wavelengths, not in the optical.

3.1. Direct Images of V1057 Cyg

If dust did form in the lower atmosphere of V1057 Cyg in 1994 and was subsequently expelled with the wind, then in time it might become detectable in scattered light. Given an ejection velocity of 200 km s\(^{-1}\) and no subsequent deceleration, then the separation of dust and star in the plane of the sky would increase at the rate of 0.070 yr\(^{-1}\), so that in the 5 yr following 1994 that dust would in projection appear about 0.35 from the star.

Five WFPC2 images of V1057 Cyg are available in the HST archive. They were obtained with HST on October 18 as part of a “snapshot” program; the filters were F606W (central wavelength 5957 A) and F814W (7940 A).

We are grateful to Karl Stapelfeldt, the principal investigator, for the opportunity to study this material. We did no more than obtain the pipeline processed images from the Archive and trim and clean up cosmic-ray hits and other defects.

Those F606W images are shown in Figure 15. There is much scattered light and spurious structure surrounding the overexposed star image, so that nothing can be said about whether structure exists as near as 0.3 from the star. However, at least three features at somewhat larger separations are present and appear to be real, judging from inspection of similar images of ordinary stars on other WFPC2 frames taken in the same series. They are identified by letters. C is the brightest; it appears as a structureless blob protruding from the star image to a distance of about 1", while A and B are fainter, curved arcs reminiscent of the larger loops at V1057 Cyg and other FUors described by Goodrich (1987).

The reality of A, B, and C is confirmed when the image of a single star (from another frame) is subtracted from the shortest F606W exposure (see Fig. 15, lower right-hand panel). Feature C is apparently only a section of an extended nebulous bar. There is no persuasive correspondence of this structure very near the star with the molecular-line maps or the 1.3 mm continuum feature north of the star described by McMuldroch (1995).

If C is a slab of warm dust very near the star, consider the possibility that its thermal emission may contribute significantly to the integrated IR emission of V1057 Cyg. An estimate of its relative contribution can be made as follows. Assume that the true separation of star and slab is as projected, 0.8 (480 AU) and that the star radiates as a blackbody of \( T_{\text{eff}} = 5300 \text{ K} \) and radius \( 9 R_\odot \). Then the equilibrium temperature of a small silicate particle exposed to that radiation field is obtained by balancing the energy absorbed by the amount reradiated. Given the absorption cross sections for “astronomical silicate” (Draine 1985), the temperature of a 0.1 \( \mu \text{m} \) silicate particle at that position is found to be about 75 K, with a weak dependence on particle radius. If the slab, an assemblage of such particles, radiates as a black surface of dimensions \( 0.33 \times 0.64 \text{ AU} \) at 75 K, then its flux would be dominant over that of the star at wavelengths greater than about 14 \( \mu\text{m} \). On the other hand, if the slab preserved the optical properties of its constituents, then the crossover wavelength would depend on particle radius, being at about 19 \( \mu\text{m} \) for 0.1 \( \mu\text{m} \) particles, at 16.5 \( \mu\text{m} \) for 0.4 \( \mu\text{m} \), and at 15.5 \( \mu\text{m} \) for 1.0 \( \mu\text{m} \). Obviously, thermal emission from such nearby dust must contribute to the spectral energy distributions (SEDs) of stars like V1057 Cyg, although to lesser degree than these estimates if the cloud were optically thick.

Dust formed in the atmosphere of V1057 Cyg and then ejected could have reached the slab’s present position in as short as 12 yr. Nothing is known of the earlier history of V1057 Cyg, but if there have been previous outbursts, each with its own dust formation episode, such distant dust concentrations might be explained. Future high-resolution imaging will show whether these structures are moving with respect to V1057 Cyg.
Unfortunately no comparable HST imagery is available at this time for FU Ori. Conventional ground-based CCD images obtained with the 2.3 m telescope on Mauna Kea show extensive reflection nebulosity around that star, with brightness increasing toward the star before merging at about 3" with the overexposed star image. Coronagraphic images reproduced by Nakajima & Golimowski (1995) extend this in to about 2.5. As at V1057 Cyg, this material and that detected at 2.3 μm very near FU Ori by Malbet et al. (1998) may contribute significantly to those SEDs.

4. FU Ori, V1057 Cyg, AND FUors IN GENERAL

4.1. Comparison with the Composite Spectrum of an Accretion Disk

Accretion disk models were devised by Kenyon et al. (1988) to explain the spectral energy distribution and the peculiar double-peak profiles of the photospheric lines in V1057 Cyg and FU Ori. In those models, the high-resolution spectra were synthesized by assuming that at any given radius the disk radiates as a stellar atmosphere of the appropriate spectral type. The variation of effective temperature with radius is given by the steady-disk theory, and the variation of the rotational velocity with radius is assumed to be Keplerian. The integrated spectrum of the disk can then be represented as a composite of annuli of different temperature, surface brightness, and rotational velocity. The models reproduce reasonably well the atomic lines in the optical region and the molecular bands in the infrared. In addition to FU Ori and V1057 Cyg, the spectrum of Z CMa was compared with the disk model by Welty et al. (1992), revealing numerous emission lines in the differential spectrum (i.e., observed minus synthetic) of Z CMa, rather as is seen in V1057 Cyg near minimum brightness.

Fig. 15.—HST images of V1057 Cyg, obtained with WFPC2 on 1999 October 18 and filter F606W (central wavelength 5957 Å). Upper left: An average of two 180 s exposures on a logarithmic intensity scale. The white bar conceals the detector bleeding of the star image; it is 3.5 long. The field size is 14.6 square. Upper right: An area of 5.5 on a side, centered on the star, from the shortest (14 s) exposure. Lower left: The same image and scale, but intensity scaled to emphasize the faint outer nebulosity (D). Features very near the star that are believed to be real are identified by letters A, B, and C. Lower right: The previous frame after subtraction of an image of a single star from another WFPC2 exposure taken in the same series. The white circle outlines the saturated central region. The diffraction spikes and much of the scattered light structure has thereby been cancelled, showing the underlying nebulosity.

Fig. 15.—HST images of V1057 Cyg, obtained with WFPC2 on 1999 October 18 and filter F606W (central wavelength 5957 Å). Upper left: An average of two 180 s exposures on a logarithmic intensity scale. The white bar conceals the detector bleeding of the star image; it is 3.5 long. The field size is 14.6 square. Upper right: An area of 5.5 on a side, centered on the star, from the shortest (14 s) exposure. Lower left: The same image and scale, but intensity scaled to emphasize the faint outer nebulosity (D). Features very near the star that are believed to be real are identified by letters A, B, and C. Lower right: The previous frame after subtraction of an image of a single star from another WFPC2 exposure taken in the same series. The white circle outlines the saturated central region. The diffraction spikes and much of the scattered light structure has thereby been cancelled, showing the underlying nebulosity.
However, not all spectral lines can be reproduced by the disk model. Some lines in regions of the spectrum not examined by Kenyon et al. are in striking contradiction to the model prediction. Because the spectrum of V1057 Cyg has changed as a result of the increasing prominence of line emission as the star has faded toward minimum brightness, in what follows we first demonstrate these discrepancies in the spectrum of FU Ori because it has not changed significantly over the last two decades.

New synthetic disk spectra were calculated for FU Ori and V1057 Cyg using the parameters of the disk models given by Kenyon et al. (1988) and a set of our own template spectra (see Table 5) obtained at the Nordic Optical Telescope with SOFIN. As an example, the synthetic and the observed spectra of FU Ori are shown in Figure 16 for the spectral range 5260–5320 Å. This synthetic spectrum looks identical to that shown in Figure 3 of Welty et al. (1992). The spectrum of FU Ori in 1998 was also very similar to that displayed by Welty et al.

In the accretion disk model for FU Ori, the relative contribution from different parts of the disk (i.e., from different spectral types) to the total flux radiated by the disk depends on wavelength as is shown in Table 6. At 5500 Å the spectrum of the disk is mostly of F–G type, while at 9000 Å all spectral types contribute about equally. This means that at 9000 Å one can find F-type along with M-type spectral features, e.g., both high-excitation lines and TiO bands.

If we consider relative line strengths, the composite spectrum of the accretion disk looks much the same as the spectrum of a normal G supergiant because the same atomic lines are changing smoothly from late-F through G to early-K types. The difference can be found only in early type F, where the lines of high-excitation species appear strongly, and in type M where molecular bands, mostly of TiO, appear very strong. Since both F and M spectral types contribute to the accretion disk model of FU Ori, we examine the observed spectrum in order to determine how these critical features behave.

The most suitable spectral region for such an analysis is around 8900 Å. It contains two Ca II lines having lower EP of 7.05 eV (8912.06 and 8927.35 Å), which are very strong only in type F, a line of V i at 8919.80 Å having EP = 1.2 eV, which increases in strength from type G to M, and a strong TiO band head at 8860 Å, characteristic of type M.

The telluric spectrum was extracted from a spectrum of the O7e fast rotator ζ Per, and with it weak terrestrial lines were removed from the FUors spectra. In order to reduce the noise, all the spectra of FU Ori taken in 1997–2000 were averaged. For V1057 Cyg, to avoid a possible contribution from the shell, only the 1998–2000 spectra were averaged because in those years the shortward-shifted TiO features were absent.

Comparison of the synthetic spectrum of the accretion disk and the observed spectrum of FU Ori is shown in Figure 17. Some of the template spectra are also displayed in the figure to show the origin of the main features in the synthetic spectrum. As expected, the synthetic spectrum of the accretion disk shows all the F- and M-type features. In the observed spectrum of FU Ori the blend at 8860 Å resembles that in the

---

**TABLE 5**

**Template Stars**

| Star  | MK Type |
|-------|---------|
| 32 Aql | F2 Ib   |
| 41 Cyg | F5 II   |
| β Aqr  | G0 Ib   |
| 9 Peg  | G5 Ib   |
| 40 Peg | G8 II   |
| 43 Tau | K2 III  |
| β And  | M9 IIIa |
| 72 Leo | M3 Iab-lb |
| 30 Her | M6 IIIa |

**TABLE 6**

**Flux Contributions to Disk**

| Type  | 5500 Å | 6400 Å | 9000 Å |
|-------|--------|--------|--------|
| F2–F7 | 0.5    | 0.4    | 0.3    |
| F8–K2 | 0.4    | 0.4    | 0.35   |
| K5–M6 | 0.1    | 0.2    | 0.35   |
| Total | 1.0    | 1.0    | 1.0    |

---

**Fig. 16.**—Comparison between the observed spectrum of FU Ori and the synthetic spectrum of the accretion disk model
synthetic spectrum, except that the TiO head is not obviously present probably on account of the overlap by Paschen line at 8862 Å. The absence of TiO is better shown in V1057 Cyg (Fig. 21, below). More obvious is the difference between the observed and synthetic spectra in the width of the Ca ii and V i lines. That region is expanded in Figure 18. In the synthetic spectrum these lines have very different widths because they originate from the innermost and from the outermost regions of the disk, respectively rotating at very different Keplerian velocities, but in the observed spectrum the lines have about the same widths.

Another example is shown in Figure 19: the high-excitation line of N i λ7442.30, EP = 10.3 eV, is strong in the F-type spectra, is present and highly doubled in the synthetic spectrum of FU Ori, but is absent in the observed one. Figure 20 shows that the ScO/TiO feature at 6036 Å is absent in the observed spectrum of V1057 Cyg or in the noisier 1998–2000 individual spectra.

Here we have considered only those spectral features detectable at the resolution of the SOFIN material. Much more could be done with spectra of higher resolution. But at the moment we conclude that comparison of the observed and synthetic spectra of FU Ori in the near infrared shows that some critical spectral features do not have the structure predicted by the multitemperature disk model, although some elaboration of that model might be able to account for the mismatches. A rapidly rotating single star will have a latitude-dependent spectrum whose appearance in integrated light will be a function of aspect angle. It remains to be seen whether such an object might produce a FUor-like spectrum.

### 4.2. Rotational Line Widths

The value of $v_{eq} \sin i$ and the nature of the photospheric line broadening in FUors have been a subject of much discussion. Welty et al. (1990, 1992) measured absorption line widths on V1057 Cyg spectrograms obtained in 1986 and 1988, when the star was brighter, and found them to depend on wavelength, being larger in the blue and smaller in the red. This they interpreted as demonstration of differential rotation in a Keplerian accretion disk, as predicted by the HK disk model.

The shortward-displaced shell spectrum had been present at some level on all our spectra of V1057 Cyg, but it is most prominent at the shorter wavelengths, where most of the low-level lines of the neutral metals are located. It was very strong in 1996–1997, so $v_{eq} \sin i$ was measured only on the 1998–2000 SOFIN spectra, and as an additional precaution, to avoid any marginal shell contribution, only the longward wings of the photospheric lines were fitted. Thirty to 40 selected lines were measured in the observed and in the synthetic model spectra of V1057 Cyg and FU Ori by comparing them with a template spectrum (β Aqr, G0 Ib) spun up to a set of discrete values of $v_{eq} \sin i$. Since the line depth in V1057 Cyg at that time was smaller than in the template, a veiling contribution (which does not affect the line width) was applied to rescale the line depths. (The average level of veiling is about 0.3. It is larger for lines filled in with emission.) The uncertainty in the measurement of a single line is...
about 5 km s$^{-1}$. The detailed results for both V1057 Cyg and FU Ori are given in Table 7.

We take as an average for V1057 Cyg $v_{\text{eq}} \sin i = 55$ km s$^{-1}$, with a scatter of individual lines from 48 to 60 km s$^{-1}$. That range is systematically larger than that from the synthetic spectrum (30–47 km s$^{-1}$), which was designed to match the spectrum of V1057 Cyg in the 1980s. Part of this difference is due to the fact that these measurements of $v_{\text{eq}} \sin i$ were made on the averaged spectra from three seasons, during which variations in the star’s radial velocity ($\pm 4.4$) could simulate line broadening. Nor can we exclude the possibility that there may have been a change of a few km s$^{-1}$ in the intrinsic line width over the years, although none is apparent between 1985 and 1997 in the profile of Fe I $\lambda 6400$ shown in Figure 10.

Our value of $v_{\text{eq}} \sin i$ (55 km s$^{-1}$) for V1057 Cyg is larger than those published by Welty et al. (1990) (35–45 km s$^{-1}$). However, they measured line half-widths at half-depth, which in a rotationally broadened profile is about 0.8 $v_{\text{eq}} \sin i$ (the precise value of the factor depending slightly upon the limb darkening assumed). We have also measured the half-widths of the red wings at half depth: the average is 44 $\pm$ 4 km s$^{-1}$, which is slightly larger than that of Welty et al., but we find no dependence of wavelength or EP.

Our values of $v_{\text{eq}} \sin i$ are plotted against wavelength and against EP in Figure 22, both for the synthetic disk spectra and as observed. The parameters of the regression lines fitted to these data are given in Table 8.

It was in V1057 Cyg that Welty et al. found their strongest evidence for a falloff of line width with wavelength and EP. Such a trend is obvious in our measurements of $v_{\text{eq}} \sin i$ in
the synthetic accretion disk spectrum, confirming the validity of that effect as a test, but no such trend is convincingly present in our measurements of the observed spectrum of that star. Given the precision of our results, it should have been detected if present. It is possible, of course, that the spectrum of V1057 Cyg has changed in these respects during the intervening decade.

The same procedure described above (fit of longward of 
v_{\text{eq}}$ sin $i$ versus $v_{\text{eq}}$ sin $i$) from zero, which could be regarded as fair evidence for a correlation in the expected sense. On the other hand, the correlation of $v_{\text{eq}}$ sin $i$ with EP, although weaker ($-0.41 \pm 0.41$), is opposite in sign to the accretion disk expectation: if real it would mean that $v_{\text{eq}}$ sin $i$ decreases with increasing EP. In the case of FU Ori, Welty et al. found essentially no dependence on wavelength, but a weak (1 $\sigma$) trend with EP, in the opposite sense to our result. This star has not changed substantially in brightness in the intervening decade, so it would seem unlikely that the spectrum has changed materially between the observations of Welty et al. and ours.

In conclusion, although the situation for FU Ori is confused, in neither FU Ori do we find persuasive evidence of the dependence of $v_{\text{eq}}$ sin $i$ on wavelength or on EP that is expected on the accretion disk hypothesis.

4.3. CO Lines

On 1999 October 24 both V1057 Cyg and FU Ori were observed in the 2.3 $\mu$m region by K. Hinkle with the Phoenix infrared spectrometer (Hinkle et al. 1998) at the KPNO$^8$ 2.1 m telescope. The region covered was 4320–4340 cm$^{-1}$ (2.315–2.304 $\mu$m) in the CO 2–0 band. These spectrograms had been obtained at the request of L. Hartmann, and we are grateful to him for access to the data and to K. Hinkle for supplying us with the reduced spectra, as well as those of several early-type stars observed on the same occasion.

This region contains many terrestrial lines, mainly of CH$_4$. These are not removed completely by standard star division because of air-mass mismatches. Instead, the value

![Graph](image_url)

**Fig. 21.**—Same as Fig. 17, but for V1057 Cyg, an average of the SOFIN spectra of 1998, 1999, and 2000, when TiO was not present in the shell. Note the absence of the TiO feature in the observed stellar spectrum.

### TABLE 7

| $\lambda$ | Ion | Low EP | $v_{\text{eq}}$ sin $i$ | V1057 Cyg | FU Ori |
|-----------|-----|--------|-------------------------|-----------|--------|
| 5316.61   | Fe  | 3.15   | 40          | 87          | 68     |
| 5569.62   | Fe  | 3.42   | 40          | 50          | 80     |
| 5572.84   | Fe  | 3.40   | 40          | 55          | 80     |
| 5581.96   | Ca  | 2.52   | 40          | 55          | 75     |
| 5853.67   | Ba  | 0.60   | 37          | 60          | 82     |
| 5862.35   | Fe  | 4.55   | 40          | 82          | 75     |
| 6003.01   | Fe  | 3.88   | 35          | 75          | 80     |
| 6024.06   | Fe  | 4.55   | 35          | 55          | 80     |
| 6027.05   | Fe  | 4.08   | 35          | 75          | 73     |
| 6056.00   | Fe  | 4.73   | 35          | 48          | 68     |
| 6065.48   | Fe  | 2.61   | 35          | 55          | 70     |
| 6141.71   | Ba  | 0.70   | 32          | 77          | 70     |
| 6180.20   | Fe  | 2.73   | 35          | 48          | 73     |
| 6191.56   | Fe  | 2.43   | 35          | 50          | 78     |
| 6347.11   | Si  | 8.12   | 45          | 60          | 92     |
| 6355.03   | Fe  | 2.85   | 37          | 48          | 72     |
| 6371.37   | Si  | 8.12   | 43          | 60          | 85     |
| 6393.60   | Fe  | 2.43   | 32          | 60          | 73     |
| 6411.65   | Fe  | 2.65   | 30          | 57          | 77     |
| 6421.35   | Fe  | 2.28   | 35          | 70          | 65     |
| 6439.07   | Ca  | 2.53   | 60          | 72          |        |
| 6546.24   | Fe  | 2.76   | 32          | 60          | 77     |

**Note.**—The units of $v_{\text{eq}}$ sin $i$ are km s$^{-1}$, and those of low EP are eV. The tabulated values of $v_{\text{eq}}$ sin $i$ are for V1057 Cyg in the years 1998–2000 and for FU Ori in 1999. The number of lines differs between the two stars because of the greater degree of blending in FU Ori.

$^8$ KPNO is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

...
of optical thickness [required to reproduce the line depth as $\exp(-\tau)$] was calculated at every pixel across these features in the standards, which was then scaled to cancel those features in the FU Ori spectra. These spectra of FU Ori and V1057 Cyg are shown in the upper rows of Figure 23. The dominant features are the broad $R$-branch lines of the CO 2–0 band [$R(19)$–$R(27)$; lower EP, 0.09–0.18 eV]. Their equivalent widths are comparable to those of early to middle M-type giants and supergiants in the atlas of Wallace & Hinkle (1996), from which the Fourier Transform spectrum (FTS) of $\lambda$ Dra (type M0 III) in the bottom section of Figure 23 has been extracted. The same spectrum spun up to $v_{\text{eq}} \sin i = 60 \text{ km s}^{-1}$ is shown just above. In $\lambda$ Dra the lines of the returning $R$-branch

![Figure 22](image_url)

**Figure 22.**—Measurements of $v_{\text{eq}} \sin i$ from Table 7, for both the observed spectra of V1057 Cyg and FU Ori (filled circles) and their synthetic disk spectra (open circles; § 4.1), plotted against wavelength (upper panels) and against lower EP (lower panels). The regression lines fitted to these data are superposed, and their parameters are given in Table 8.

### TABLE 8

| Parameter          | V1057 Cyg | FU Ori | V1057 Cyg | FU Ori |
|--------------------|-----------|--------|-----------|--------|
|                    | Disk      | Observation | Disk      | Observation |
| $A$                | 39.078    | 56.082 | 76.816    | 80.620 |
| $\sigma(A)$        | 4.175     | 6.165 | 7.018     | 4.402  |
| $B$                | -0.423    | -0.262 | 0.061     | -1.345 |
| $\sigma(B)$        | 0.601     | 0.894 | 1.006     | 0.640  |
| $r$                | -0.112    | -0.058 | 0.010     | -0.330 |
| $n$                | 41        | 27     | 38        | 38     |
| $P_c$              | 0.486     | 0.772 | 0.952     | 0.043  |

**Dependence of $v_{\text{eq}} \sin i$ on Wavelength**

**Dependence of $v_{\text{eq}} \sin i$ on Lower EP**

**Note.**—The regression lines are of the form $v_{\text{eq}} \sin i = A + Bx$, where $x$ is $\lambda/1000$ or lower EP (in eV), $n$ is the number of points fitted, and $r$ is the linear correlation coefficient.

$^a$ Values of $P_c$ are the probability that the data could have come from an uncorrelated parent population; i.e., a small $P_c$ suggests that a significant correlation exists (see Press et al. 1986).
[R(75)–R(81): lower EP, 1.33–1.55 eV] are strong, but they are not apparent in either FUor. Although they would be masked to some degree by the greater line widths, the lack of convincing and consistent asymmetries in the FUor lines due to these blends suggest a lower rotational temperature.

The CO lines have different shapes in the two FUors: in FU Ori they are broad and essentially symmetric, while in V1057 Cyg they are asymmetric, with a narrow core and an extended wing toward negative velocities. To reduce the effects of instrumental noise and that introduced by atmospheric line removal, the line profiles shown in Figure 24 were created by averaging the 4–5 least noisy CO lines for each star. These were fitted by a procedure similar to that described in § 2.3. The instrumental profile, represented by that of a narrow atmospheric CH$_4$ line of FWHM = 8 km s$^{-1}$, could be spun up to adjustable $v_{\text{eq}} \sin i$, central velocity, and central depth. The parameters of the fits are given in Table 9. Although the off-center structure in FU Ori may be real, a single component serves to represent the overall profile reasonably well. In the case of V1057 Cyg, the observed profile is certainly not a narrower version of the stellar absorption lines. Formally, it can be fitted to two overlapping, rotationally broadened copies of the atmospheric line. Because of the complex structure, comparison of these $v_{\text{eq}} \sin i$’s with the optical value cannot be very meaningful.

In neither star is there any evidence of shell structure at large negative velocities, perhaps understandably because the shell spectrum in the optical was very weak at the time of the CO observation. The CO velocity of FU Ori agrees closely with the conventional velocity of that star (+28 km/s).

**Fig. 23.** Top: Spectra of V1057 Cyg and FU Ori in the 2.3 $\mu$m region, as observed by K. Hinkle on 1999 October 24. They have been smoothed by a 5 pixel box and corrected for their nominal optical-region velocities. The FTS spectrum of $\lambda$ Dra (M0 III) from the atlas of Wallace & Hinkle (1996) has been slightly smoothed (bottom) and spun up to $v_{\text{eq}} \sin i = 60$ km s$^{-1}$. (above).

**Fig. 24.** Mean CO profiles for V1057 Cyg (average of five lines) and FU Ori (average of four lines). The vertical solid lines show the ±1 standard deviations of each mean point. The vertical dashed line indicates the optical velocity of each star.

**TABLE 9**

| Star        | Component | $v_{\text{eq}} \sin i$ (km s$^{-1}$) | $v$ (km s$^{-1}$) | $A_e$ |
|-------------|-----------|-------------------------------------|-------------------|-------|
| V1057 Cyg...| 1         | 12.                                 | -26.              | 0.085 |
|             | 2         | 45.                                 | -35.              | 0.15  |
| FU Ori......| 1         | 48.                                 | +27.              | 0.105 |

Note.—$A_e$ is defined in Table 1.
s\(^{-1}\)), in agreement with Mould et al. (1978), who found \(\pm 28.2 \pm 2.5\ \text{km s}\(^{-1}\)) from several CO and metal lines. However, the velocities of both CO components of V1057 Cyg (Table 7) are displaced from the optical \(-16\ \text{km s}\(^{-1}\)) and they do not agree with the Mould et al. value of \(-13.4 \pm 3.5\ \text{km s}\(^{-1}\)).

In the case of FU Ori, the value of \(v_{\text{eq}} \sin i\) from CO (48 km s\(^{-1}\)) is clearly smaller than that we obtain from the optical region (70 km s\(^{-1}\)), in the same sense as earlier work by the CfA group. Hartmann & Kenyon (1987a) measured total widths of cross-correlation peaks rather than values of \(v_{\text{eq}} \sin i\), so the two results cannot be compared directly, except to say that they found the CO lines in FU Ori to be narrower than the optical by a factor of about 0.75, as compared with our 0.69. In V1057 Cyg also, the stronger CO component (45 km s\(^{-1}\)) is narrower than the optical total \(v_{\text{eq}} \sin i\) of 55 km s\(^{-1}\), but this may not be significant because the CO profiles are peculiar. The only published CfA result for CO in V1057 Cyg is an estimate that \(v_{\text{eq}} \sin i\) is about 20 km s\(^{-1}\) (Hartmann & Kenyon 1987b).

4.4. Search for Rotational Modulation in Line Profiles

In TTSs a period of axial rotation can be derived from rotational modulations of brightness and line profiles caused by surface inhomogeneities (cool or hot spots) and nonaxisymmetric structure of the wind (see, e.g., Petrov et al. 2001). Unlike an ordinary star, an accretion disk has no single rotational period but a range of Keplerian orbital periods. In the accretion disk models for FU Ori and V1057 Cyg (Kenyon et al. 1988), the Keplerian periods range from 3–4 days for the inner disk where the F-type spectrum is formed, to 30–40 days for the outer regions contributing to the M-type spectrum. Thus an observational test would be to search for rotational modulation in the wind, emission, and photospheric line profiles. The most prominent wind feature is the H\(_\alpha\) P Cyg line. The emission lines of metals are present only in the spectrum of V1057 Cyg and are too weak to be used in such an analysis because the individual spectra of V1057 Cyg near minimum brightness are rather noisy. The photospheric lines, although also being weak, can, however, be analyzed by cross-correlation, which compensates for the poor signal-to-noise ratio of the individual spectra.

4.4.1. Wind Profiles

Figure 25 shows overplotted all the H\(_\alpha\) profiles from the SOFIN data of 1996–2001 for V1057 Cyg. Figure 26 shows the H\(_\alpha\) profiles of FU Ori in 1995–2001, but separated in two parts to emphasize the major changes in the longward emission component. The left-hand panel is a superposition of all the profiles in which the emission peak intensity was greater than 1.20 (in continuum units), and the right-hand panel all those with peak less than 1.10. As already mentioned, there is no obvious correlation between these emission peak intensities and the extension of the P Cyg absorption component to negative velocities.

The timescale of the variability is different in the two objects. In V1057 Cyg, the night-to-night variability is relatively small, but the average profile is quite different in different years (see also Fig. 7). In both objects, most variable is the central emission peak and the portion of the profile between about \(-100\) and \(-400\ \text{km s}\(^{-1}\)).

The same variations are seen in the P Cyg absorptions of the Na \(_i\) D\(_{1,2}\) lines, which correlate well with H\(_\alpha\), although the Na \(_i\) lines have a somewhat smaller range in wind velocity. The absorption at the infrared Ca \(_ii\) lines also vary together with H\(_\alpha\) and Na \(_i\), but the velocity amplitude is much smaller. H\(_\alpha\) was chosen for analysis because it showed the largest range in wind velocity.

In FU Ori, the line profiles change considerably on a timescale of a day (as was noted most recently by D’Angelo et al. 2002a, who give earlier references). The following variability patterns are seen in the H\(_\alpha\) profile on SOFIN spectra: (1) There is no correlation between the changes of the absorption and emission components (we return to this matter in the following section). (2) Three sections of the absorption component vary independently of one another: (a) a “slow wind” at RV = \(-50\) to \(-110\ \text{km s}\(^{-1}\)), (b) a “fast wind” at \(-110\) to \(-270\ \text{km s}\(^{-1}\)), and (c) an even faster wind at \(-270\) to \(-400\ \text{km s}\(^{-1}\)). (3) The fast wind portion shows quasi-periodic variations in EW, but (4) no periodicity is found in the emission component of H\(_\alpha\).

The dense time coverage of the SOFIN spectroscopy makes feasible a search for periodicity, so the EW of the P Cyg absorption between \(-110\) and \(-270\ \text{km s}\(^{-1}\)) was used as a parameter of the fast wind of FU Ori. Those EWs are listed in Table 10. The phase dispersion minimization method (Stellingwerf 1978) was used to search for periodicity in these data. When the velocities of only three seasons, 1997–1999, are examined (20 nights), the periodogram (Fig. 27, \textit{upper panel}) shows a group of significant peaks at 13–18 days, with the most probable value being 14.847 days. Fisher’s method of randomization (Linnell Nemec & Nemec 1985) gives a false alarm probability (FAP) of less than 0.01 for that period. There are no other significant periods between 2 and 100 days. The phase diagram (Fig. 27, \textit{lower panel}) shows that period is defined largely by the 1997 and
1998 data. The data of 1999 also fit, but they span a shorter phase interval. The periodicity is not present in the data of 2000 (7 nights) although the fast wind EW varied over almost the same range.

Errico, Vittone, & Lamzin (2003) have recently published Hα/C11 profiles of FU Ori obtained over 5 consecutive nights in 1999 January. The variations in the P Cyg absorption (measured by them as velocity width at an intermediate depth) indicated that if periodicity was present, the period could be about 6–8 days, shorter by a factor 2 than found from our more extended set of EW measurements. Considering that our observations in 2000 show no periodicity, it may be that the 14.8 day cycle had already become undetectable in 1999. Our own data of October 1999 (4 nights) are too limited to pronounce upon the presence of a 6–8 day cycle in that year. We conclude that the variations of the wind absorption in FU Ori are quasi-periodic: in 1997–1998 the period was 14.8 days but that periodicity had disappeared by 2000.

Errico et al. suggested that these cyclic variations in the wind of FU Ori are caused by the interaction of the stellar magnetic field with the disk outflow, assuming that the magnetic axis of the star is inclined to the disk rotational axis. However, in that model of an inclined magnetic rotator one would expect rather stable periodicity on a very long timescale. Instead, the quasi-periodic character of the variations is more like that observed in TTS, where surface inhomogeneities (spots) may appear and disappear due to changes in the star’s magnetic field structure.

### TABLE 10

| JD – 2,450,000 | EW (Å) | JD – 2,450,000 | EW (Å) |
|----------------|--------|----------------|--------|
| 0054.539       | 1.478  | 1092.721       | 2.035  |
| 0055.575       | 1.177  | 1093.704       | 2.206  |
| 0795.647       | 2.114  | 1094.713       | 1.999  |
| 0796.676       | 2.007  | 1471.693       | 0.774  |
| 0798.665       | 1.805  | 1472.722       | 0.516  |
| 0799.706       | 1.432  | 1473.689       | 1.144  |
| 0802.678       | 0.831  | 1475.717       | 1.808  |
| 0804.697       | 0.897  | 1887.569       | 1.231  |
| 0806.678       | 1.701  | 1888.527       | 1.133  |
| 0807.695       | 1.530  | 1889.571       | 1.745  |
| 0890.399       | 1.229  | 1890.572       | 1.000  |
| 1088.672       | 1.504  | 1892.573       | 1.308  |
| 1089.706       | 1.759  | 1893.568       | 1.308  |
| 1090.704       | 1.890  | 1896.572       | 0.755  |
| 1091.706       | 1.843  | ...            | ...    |

**Note.**—The equivalent widths are for the section of the absorption line between RV = –110 and –270 km s\(^{-1}\).
We suggest that the longer period of 14.8 days suggested by the H\(\alpha\) variations (because that line showed the largest velocity amplitude) is the rotational period of FU Ori. In case the wind is governed by the star’s magnetic field (as is believed to be the case in TTS), a relatively stable axial asymmetry of the field structure might cause the observed rotational modulation over at least 2 yr (1997–1998), or 50 rotational cycles. The observed \(v_{\text{eq}} \sin i = 70 \text{ km s}^{-1}\) then leads to a value of \(R \sin i = 20.4 \, R_\odot\).

In the accretion disk model for FU Ori (Kenyon et al. 1988) a period of 14.8 days corresponds to a Keplerian orbit of radius 20 \(R_\odot\), where the K-type spectrum is supposed to be formed, but it is not clear why a global disk wind should be modulated with any single period.

If the intrinsic optical colors of FU Ori are those of a normal G0 Ib, then the observed values for the 2000 season \((V = 9.58, \, V-R_J = +1.185)\) correspond to \(E(V-R)_J = 0.575\), so if the reddening is normal, the average \(A_V\) is 1.38 mag, leading to \(M_V = -0.1\) for the assumed distance of 450 pc. The visual flux in solar units is

\[
\frac{F_V}{F_V(\odot)} = 2.512^{-M_V + M_V(\odot)}.
\]

If only a fraction \(x\) of the surface is occupied by regions having the G0 Ib brightness, then the radius of such a spherical star is

\[
R = \left(\frac{F_V}{F_V(\odot) x b} \right)^{1/2} R_\odot,
\]

where \(b = 0.7\) is the ratio of surface brightnesses at \(V\) calculated by the procedure of Barnes et al. (1976). If \(x = 1\), the result is that \(R = 11.3 \, R_\odot\).

Consider whether this last result can be reconciled with \(R \sin i = 20.4 \, R_\odot\). If the star’s surface brightness is not uniform, then any value of the coverage factor \(x \leq 0.32\) could bring the two into agreement, the inclination then following from \(\sin i = (20.4/11.3)^{1/2}\).

Another possibility: if the \(A_V\) inferred from the color excess of FU Ori were ignored and instead taken to be 2.66 mag, regarded as the sum of conventional interstellar reddening in the foreground and a circumstellar component of unspecified reddening properties, then \(M_V\) would become \(-3.4\) and \(R = 20.4 \, R_\odot\), in agreement with the axial rotation result for \(\sin i = 1\). If the entire \(A_V\) was circumstellar, then \(A_V/E(B-V) = 5.4\), compared with the normal interstellar value of 3.1. \(A/E\) ratios greater than about 4.0 are not unprecedented, having been found in dusty H\(\alpha\) regions and in dense molecular clouds (Cardelli, Clayton, & Mathis 1989; Chini & Wargau 1998), there usually being ascribed to the presence of larger particles. That may not be inconceivable in the case of FU Ori because the local reddening of such a dusty object need not obey the normal interstellar extinction law. But there must surely be a normal interstellar contribution to \(A_V\), in which case the \(A/E\) ratio of the circumstellar component would become even larger, as it also would if \(\sin i < 1.0\) for FU Ori.

So either hypothesis could reconcile the two results. We see no strong observational reason to favor one hypothesis over the other at this time, except that the dust explanation does require circumstellar extinction of unusual properties. The periodic variation in wind strength observed in FU Ori, with its implication of unevenly distributed active areas, favors the blotchy surface hypothesis. If precise photometry showed that FU Ori varies cyclically with that same period, it would strengthen that proposition. Dust formation low in the atmosphere, leading to a larger \(A_V\) and an abnormal \(A/E\) and subsequent ejection, might explain dust structure very near the star. But at this time the question remains open.

4.4.2. Photospheric Profiles

As remarked earlier, the double-peaked profiles of (some) photospheric lines have been used as one of the arguments in support of the accretion-disk model of FUors (HK). So far, no spectral time series have been available to determine how stable is this peculiar line structure, which we attribute (§ 2.4) to the presence of emission cores in the low-excitation lines. In our spectral series of V1057 Cyg and FU Ori (SOFIN data of 1995–2001) this line structure is found to be variable on a timescale of several days. In the following we use the cross-correlation method to give information about line profiles averaged over a certain spectral region, usually one spectral order. The spectrum of \(\beta\) Aqr (G0 Ib) is used as a template.

As an example, Figures 28 and 29 show night-to-night variability of the cross-correlation functions (CCF’s) during one set of observations of V1057 Cyg and FU Ori. The CCF profile varies synchronously in different spectral regions: the line width at half-depth remains about the same, while the central part varies with either shortward or longward peak being stronger, sometimes becoming single and quite

![Cross-correlation functions showing night-to-night variability in the photospheric line profiles in V1057 Cyg over eight consecutive nights of 1997 August.](image-url)
symmetric. Of course the CCF profile depends on the particular mix of low- and high-excitation lines in the sample, and this may be why different spectral orders show somewhat different CCF shapes, but the variations are similar in different orders. The spectral intervals selected for cross-correlation were chosen to avoid lines with shell
different orders. The spectral intervals selected for cross-
correlation were chosen to avoid lines with shell

As a descriptor of line position we use the “center of
gavity” of the CCF, namely, its weighted mean radial
velocity. This is the velocity of the star as if it had been
measured from the “center of gravity” of a photospheric
line profile, although variations of this quantity do not nec-
asarily mean that the whole star moves around in radial
velocity.

In the case of V1057 Cyg two spectral orders (6320–6440
and 6575–6640 Å) were combined; the resulting precision
of RV is about ±3 km s\(^{-1}\). The spectra of FU Ori are of better
quality, so six spectral orders (from 5560 to 7520 Å) were
used, the resulting precision being ±1 km s\(^{-1}\). Table 11
contains the measured RV’s for both stars.

Since the individual CCFs are quite noisy, especially for
V1057 Cyg, three groups of CCFs showing similar RVs
were selected: shortward-shifted, centered, and longward-
shifted. The three CCFs shown in Figure 30 are averages for
these three groups, overplotted to illustrate typical varia-
tions of the CCF profile. For V1057 Cyg each CCF is an
average of eight spectra, for FU Ori each is an average of
four. Obviously, the main source of the variability is the
deformation of the central part of the line profile: the ratio
of shortward-to-longward peak intensity is variable, while

The width of the line remains about the same. This latter fact
excludes the possibility of a double-line binary, where the
line width must be narrower when the two components have
the same radial velocity.

For FU Ori, the periodogram shown in the upper panel
of Figure 31 was calculated using the data of the 1997, 1998,
and 1999 seasons (20 nights). The most probable period is
3.542 days, with FAP < 0.01. When phased with this
period, the lower panel of Figure 31 shows the cyclic vari-
ation of RV in these 3 yr. The semiamplitude of the sinusoi-
dal variations of RV is 1.8 km s\(^{-1}\). The scatter of points
around the sinusoidal curve is less than ±1 km s\(^{-1}\), which
must be entirely due to the errors in RV. When all the data

---

**TABLE 11**

| V1057 Cyg          | FU Ori          |
|--------------------|-----------------|
| JD −2,450,000      | JD −2,450,000  |
| RV (km s\(^{-1}\)) | RV (km s\(^{-1}\)) |
|--------------------|-----------------|
| 387.448            | 54.538          |
| 676.572            | 55.575          |
| 677.395            | 795.647         |
| 678.402            | 796.676         |
| 679.395            | 798.665         |
| 680.384            | 798.705         |
| 681.384            | 802.677         |
| 682.383            | 804.697         |
| 683.405            | 806.678         |
| 997.472            | 807.694         |
| 999.601            | 809.398         |
| 1000.562           | 1088.672        |
| 1002.532           | 1089.706        |
| 1003.546           | 1090.703        |
| 1005.521           | 1091.706        |
| 1008.545           | 1092.721        |
| 1383.554           | 1093.704        |
| 1384.603           | 1094.713        |
| 1385.556           | 1471.693        |
| 1386.550           | 1472.722        |
| 1387.515           | 1473.689        |
| 1388.529           | 1475.717        |
| 1389.522           | 1887.569        |
| 1390.555           | 1888.527        |
| 1391.524           | 1889.571        |
| 1392.552           | 1890.572        |
| 1393.586           | 1892.573        |
| 1394.561           | 1893.568        |
| 1764.606           | 1896.572        |
| 1765.611           | 1897.572        |
| 1766.599           | 1898.572        |
| 1767.609           | 1899.572        |
| 2120.480           | 2121.493        |
| 2121.493           | 2122.571        |
| 2122.571           | 2124.495        |
| 2124.495           | 2125.540        |
| 2125.540           | 2127.595        |
| 2127.595           | 2128.595        |
| 2128.595           | 2130.564        |
| 2130.564           | 2131.501        |

**Note.**—RV is the measured radial velocity minus the radial velocity of the star: −16 km s\(^{-1}\) for V1057 Cyg and +28 km s\(^{-1}\) for FU Ori.
of 1995–2000 are used (29 nights), the period is still present but the data of 2000 are not well fitted to the sinusoidal curve. It is concluded that the period of 3.542 days in the photospheric lines of FU Ori was stable during at least 3 yr.

For V1057 Cyg, using all the data of 1995–2001 (42 nights), the periodogram reveals a group of peaks around 4.4–4.5 days, with the most probable period being 4.43 days. However, the semi-amplitude of the RV variations (3 km s\(^{-1}\)) is comparable with the errors in RV (3 km s\(^{-1}\)), which makes it unlikely that the periodicity is real, so we draw no conclusions from this result.

The nature of such variations in the photospheric line structure is not clear. In the case of a single star, variations like those shown in Figure 30 can be caused by an asymmetric polar starspot. However, a dark spot must also modulate the apparent stellar brightness. No such variation has been reported for FU Ori. Since the photospheric line doubling is due to the presence of emission cores, variations in the doubling may be caused by movement of those cores. It is also possible that the line emission originates from a volume of gas distributed non-axisymmetrically around the star. Such “emission spots” could also produce a rotational modulation of the photospheric line profile. On the other hand, if the wind cycle of 14.8 days is the rotational period, it is hard to explain why the period of the photospheric variations is 4 times shorter.

In case of the accretion disk model (Kenyon et al. 1988), a period of 3.542 days corresponds to Keplerian rotation at a distance of 7.7 \(R_\odot\) (if the mass of the central star is 0.5 \(M_\odot\)). This is the innermost part of the disk, where the F-type spectrum is supposed to be formed. If variability of the photospheric lines is caused by some kind of brightness asymmetry in the disk, the stability of such an asymmetry over 3 yr (300 orbital periods) would be difficult to understand in a differentially rotating disk.

Apart from the deformation of the line profiles, small shifts of the CCF can be noticed in V1057 Cyg (Fig. 30): the change in the shortward-to-longward peak intensity is accompanied by shifts of the entire CCF profile by a few km s\(^{-1}\). If these shifts are real, and not an artifact of cross-correlating noisy spectra, it could indicate the presence of a low-mass secondary near the star. Series of better quality spectra are needed to check whether this effect is really present.

Unruh, Collier Cameron, & Guenther (1998) have inferred the presence of hot spots on the rotating TTS DF Tau by an analysis of such cyclic deformations of absorption line profiles. Those hot spots, which they suggest are accretion shocks at mass-infall points, are clearly hotter than any of those on the classical FUors, where there is no sign of the He \(\text{i}\) lines at 5875 or 7065 Å in emission.

### 4.5. Infall

Our new spectroscopic material refutes a concern that we raised in 1992, namely, that there was then no direct spectroscopic evidence of infall in FUors, such as “reversed P Cyg” structure. Disk theory yields an accretion rate onto...
the FUor central star of about $10^{-4} M/M_\odot$ yr$^{-1}$ (Hartmann & Kenyon 1996), as compared with $\approx 10^{-3} M/M_\odot$ yr$^{-1}$ for classical T Tauri stars (CTTS). One would think that the movement of such massive amounts of material on to the star would surely be detectable.

The disk hypothesis has been extensively elaborated since HK and a number of possible explanations have been offered for the lack of evidence for infall: (1) much of the accreted material may be ejected from the disk surface as wind and so never reach the star, (2) the accreting mass may accumulate in the disk, (3) the central source may be so faint that absorption lines would not be detectable against its continuum, (4) the disk may be so thick at its inner edge that any activity nearer the star is concealed (in fact Kley & Lin [1996] predict that at an accretion rate of $10^{-4} M/M_\odot$ yr$^{-1}$ “the entire stellar surface is engulfed by opaque disk gas”), or (5) an optically thin infall region may be hidden not because of disk thickness but because these FUors are observed at unfavorable aspect angles.

However, as a result of the detailed time coverage at SOFIN, evidence of what appears to be sporadic infall onto the continuum source can now be seen in the Hα profiles of both FU Ori and V1057 Cyg. On two (of 29) SOFIN spectra a weak absorption component appeared at about RV = +90 km s$^{-1}$ in the longward wing of Hα. Figure 32 shows three of these spectra, demonstrating that the feature was present on JD 2,450,796.68, but not at comparable strength on the day before or 2 days later. The pattern was the same at Hβ, and the absorption was marginally detectable at the Na i D$_{12}$ lines, but not at the O i λ7773 blend, which in CTTS is sensitive to accretion. A similar absorption had appeared at Hα at about the same velocity on JD 2,450,807.69 but had been absent on the day before. Clearly, these infall features in FU Ori vary rapidly in strength, on a timescale of 1 day or less. The longward wing of the absorption in Hα extends to about +150 km s$^{-1}$, which is near the free fall velocity at the surface of a star of 1 solar mass and a radius of 20 $R_\odot$. A similar event has been seen in a HIRES observation of FU Ori in early 2003.

It is uncertain if the complete suppression of the longward component of Hα as seen in the right-hand panel of Figure 26 can be ascribed to very heavy accretion of this kind.

Thus infalling material does appear sporadically in the line of sight to both FU Ori and V1057 Cyg, as is observed in many CTTS (Edwards et al. 1994). It is there thought to be due to magnetically channeled, free-falling disk material. A signature of such magnetospheric accretion is the presence of emission lines of He i and He ii that are believed to originate in the hot spots where infalling material impacts the star (Beristain, Edwards, & Kwan 2001). As already noted, no such emission lines appear in any of our spectra of the classical FUors.

It has been suggested that in CTTS a consequence of such infall may be the ejection of Herbig-Haro (HH) like jets, and it is interesting that the spacing of structure in some HH outflows does correspond to estimates of the time spacing of repetitive FUor events in TTS. A signature of such shocked gas is the presence of lines of [O i], [S ii], and sometimes [N ii] (Cabrit et al. 1990). All that we have found in the integrated spectra of the FUors that we have observed are the very weak, broad [O i] and [Fe ii] emissions in V1057 Cyg (§2.4). They have large negative velocities and so must be formed in the outflowing wind. The [S ii] or [N ii] lines are not detected, although they would be expected to be much weaker. However, no HH-like jets are seen in the direct images of the FUors we have observed, although a search at higher angular resolution with the proper filters would be worthwhile.

4.6. The Ca ii H and K Lines in FUors

An unusual feature of the preoutburst spectrum of V1057 Cyg was that although the K line (λ3933) of Ca ii was strong in emission, the H line (λ3968) was absent. The obvious explanation of this oddity, as was realized long ago, is that λ3968 is quenched by the P Cyg absorption component of He λ3970. Important conclusions are (1) that 12 yr before the 1970 flare-up, V1057 Cyg was subject to a strong mass outflow, i.e., the high-velocity wind did not turn on at the time of the outburst, and (2) that wind was seen against the spectrum of the preoutburst star.

The same anomaly was also present 28 yr after the flare-up: a HIRES spectrogram obtained 1998 October 30, when the star was about 1 mag (in B) above minimum brightness, is shown in Figure 33. It not only demonstrates that the He wind is indeed responsible for the K : H anomaly but also implies that such a wind may be a quasi-permanent characteristic of the object.

This same wind suppression of Ca ii λ3968 has been observed in FU Ori since the time of the first adequate spectroscopy (1948). It is seen not only in the other classical FUor that we have observed (V1515 Cyg) but also in Z CMa, which has been called a FUor, as well as in V1331 Cyg, to which attention was called long ago by Welin (1971) for that very reason. Only BBW 76 (Reipurth 1990, 1997; Reipurth et al. 2002) does not conform: narrow emission is present in both Ca ii lines. Figure 33 shows HIRES spectra of the 3900–3980 Å region for all six stars. The presence of
strong Ca ii emission in all the FUors, both near or below maximum light, shows that a permanent chromosphere is characteristic of the group.

This K : H anomaly is not a common feature of TTS spectra. Most TTS outflows occur at modest negative velocities such that the absorption component at H\(\alpha\) falls within the broad underlying emission line: see the atlases of H\(\alpha\) profiles by Fernández et al. (1995) and by Reipurth, Pedrosa, & Lago (1996). FUor outflows are dramatically different in that the mass involved is much larger and extends to much greater negative velocities; hence the characteristic P Cyg profile and the suppression of H\(\epsilon\). If this K : H anomaly is indeed a FUor signature, can it be that there are unrecognized FUors among the host of ordinary TTS? There are 65 stars with Ca ii emission in the atlas of TTS spectra by Valenti, Basri, & Johns (1993), and of these only three (AS 353A, LkH\(\alpha\) 321, V1331 Cyg) have the Ca ii \(\lambda3968\) line suppressed. The spectra of three additional stars apparently showing the same effect have been published by Pereira et al. (2001). Detection of such stars by slitless spectroscopy would be an efficient means of searching for new FUor candidates.

4.7. Does the FUor Phenomenon Occur in Every T Tauri Star?

Before the 1970 outburst, V1057 Cyg was only one of some 50 faint H\(\alpha\)-emission stars scattered over the NGC 7000–IC 5070 region. Since it seemed to be just another TTS—on the slender evidence of that single preoutburst low-resolution slit spectrogram—it was suggested in Herbig (1977) and then again in Herbig (1989) that such outbursts might be a characteristic of TTSs in general. If so, from the number of such outbursts that had been detected (three at
that time) and a guess as to how many TTSs exist within an observable distance around the Sun, it was estimated that “the mean time between successive FU Ori–like outbursts in an individual T Tau star” is about $10^4$ yr. That estimate has since been refined by others but the basic concept has survived.

As appealing as that idea and the way it can be worked into a larger picture of pre–main-sequence evolution (Hartmann & Kenyon 1996) is, it was a pure conjecture. Consider these points:

First, if every TTS is a potential and presumably recurrent FUor, then FUors would be expected to appear in clusters or associations rich in TTSs. None of the classical FUors occur in the Orion Nebula, around ρ Oph, or in other regions containing large numbers of TTSs. V1057 Cyg lies in an isolated dark cloud containing only one other very faint Hα emitter,9 and no other TTSs have been found in the elongated streamer northwest of IC 5146 where V1735 Cyg is located, while V1515 Cyg is one of several Hα emitters scattered over an extended obscured region. BBW 76 is alone in a small dark cloud, with no known TTSs in the vicinity. There are exceptions, however: there are a number of TTSs near the small dark cloud B35 in which FU Ori lies, and the heavily obscured L1551 IRS 5 is located in a loose grouping of TTSs at the southern edge of the Taurus clouds.

Another possible exception may be the candidate FUor CB 34V, which, according to Alves & Yun (1995), appears to lie on the near side of a heavily obscured aggregate of young stars.

Second, it was pointed out above (§ 4.6) that at minimum light, some 12 yr before the outburst, V1057 Cyg exhibited the same strong outflowing wind that it has shown ever since the flare-up. The same P Cyg structure at Hα is found in other FUors observed near maximum light. Such vigorous mass ejection is not a property of ordinary TTSs, although some TTSs are also rapid rotators: four of some 60 TTSs listed by Hartmann & Stauffer (1987) noted that all the FUors recognized at that time (and FU Ori (70 km s$^{-1}$) are narrower than are optical lines shortward of 0.9 μm; the situation for V1057 Cyg is uncertain. Whether this is unarguable support for the disk hypothesis is not clear: it would be interesting to determine if the same effect appears in the CO lines of normal G supergiants. We believe that it is they that caused those absorption lines to appear double when the star was brighter. Presumably such chromospheres are present in the other classical FUors as well, judging from the ubiquity of Ca II λ3933 emission. The presence of a chromosphere is not in itself evidence against the disk hypothesis: the chromosphere could equally well be on the disk surface as on the rapid rotator.

2. We have been unable to confirm the dependence of $v_{eq} \sin i$ upon either wavelength or lower EP that has been urged as evidence for the accretion disk model. However, we do agree that the CO lines in the 2 μm region of FU Ori are narrower than are optical lines shortward of 0.9 μm; the situation for V1057 Cyg is uncertain. Whether this is un

3. Synthetic disk spectra that resemble FUors at optical wavelengths fail to match certain critical lines in the near infrared, indicating that syntheses such as those described in § 4.1 can no longer be regarded as firm support for the disk hypothesis, although some elaboration of that hypothesis might reduce the discrepancies.

The point is that we find that some of the observational evidence that has been offered in support of the disk hypothesis can either be explained in another way or cannot be confirmed. Although details are somewhat

9 It is the star indicated by an arrow in Fig. 1a of Duncan, Harlan, & Herbig (1981).
different, the proposal of Petrov & Herbig (1992) and of Herbig (1989) is strengthened, namely, that the observable properties of the classic FUors are better explained by a single star rotating near the limit of stability and losing mass via a powerful wind, as was originally proposed by Larson (1980).

On slender evidence, V1057 Cyg is assumed to have been a classical TTS before the 1970 outburst. Although by 1999 it had declined to about 1.5 mag (in B) above minimum, the spectrum still (by 2002) has not begun to resemble that of a conventional CTTS. In time it may do so, and some of the issues raised here may be resolved. Meanwhile, it is important that the star be monitored spectroscopically on a regular basis.

REFERENCES

Alves, J., Hartmann, L., Briceño, C., & Lada, C. J. 1997, AJ, 113, 1395
Alves, J. F. R. Inf. Bull. 1995, ApJ, 438, L107
Barnes, T. G., Evans, D. S., & Parsons, S. B. 1976, MNRAS, 174, 503
Bastien, U., & Mundt, R. 1985, A&A, 144, 57
Bell, K. R. 1999, ApJ, 526, 411
Bell, K. R., Lin, D. N. C., Hartmann, L. W., & Kenyon, S. J. 1995, ApJ, 444, 376
Bieristain, G., Edwards, S., & Kwan, J. 2001, ApJ, 551, 1037
Bouvier, J., Bertout, C., Benz, W., & Mayor, M. 1986, A&AA, 165, 110
Cabrit, S., Edwards, S., Strom, S. E., & Strom, K. M. 1990, ApJ, 354, 687
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Chini, R., & Wargau, W. F. 1980, A&A, 329, 888
Clarke, C. J., Lin, D. N. C., & Pringle, J. E. 1990, MNRAS, 242, 439
Croswell, K., Hartmann, L., & Avrett, E. H. 1987, ApJ, 312, 227
D’Angelo, G., Gomez, M. T., Smaldone, L. A., & Vittone, A. A. 2000a, A&A, 356, 888
D’Angelo, G., Gomez, M. T., Errico, L., Smaldone, L. A., & Vittone, A. A. 2000b, Mem. Soc. Astron. Italiana, 71, 1037
Draize, B. T. 1985, ApJS, 57, 587
Duncan, D. K., Harlan, E. A., & Herbig, G. H. 1981, AJ, 86, 1520
Edwards, S., Hartigan, P., Ghandour, L., & Andrulis, C. 1994, AJ, 108, 1056
Elías, J. H. 1978, ApJ, 225, 859
Errico, L., Vittone, A. A., & Lanzini, S. A. 2003, Astron. Lett., 29, 105
Fernández, M., Ortiz, E., Eiroa, C., & Miranda, L. F. 1995, A&AS, 114, 439
Goodrich, R. W. 1987, PASP, 99, 116
Haro, G. 1971, in Pre-Main-Sequence Objects, ed. B. Reipurth (Garching: ESO), 233
Hartmann, L., & Kenyon, S. J. 1985, ApJ, 299, 462 (HK)
—–1987a, ApJ, 312, 243
—–1987b, ApJ, 322, 393
—–1996, ARA&A, 34, 207
Hartmann, L., & Stauffer, J. R. 1989, AJ, 97, 873
Herbig, G. H. 1958, ApJ, 128, 259
—–1977, ApJ, 217, 693
—–1989, in ESO Workshop on Low-Mass Star Formation and Pre-Main-Sequence Objects, ed. B. Reipurth (Garching: ESO), 233
Hinkle, K. H., Cuberley, R., Gaugham, N., Heynsens, J., Joyce, R., Ridgway, S., Schmitt, P., & Simons, J. E. 1998, Proc. SPIE, 3354, 810
Ibrahimov, M. 1996, Inf. Bull. Variable Stars 4494
Kopatskaya, E. N. 1984, recr.20, 263
Kopatskaya, E. N., Grinin, V. P., Shakhkovskoy, D. N., & Shulov, O. S. 2002, Astrofizica, 45, 175
Laakkonen, T. 2000, in Proc. 33rd ESLAB Symp., ed. F. Favata, A. A. Kaas, & A. Wilson (ESA SP-445; Noordwijk: ESA), 445
Larson, R. B. 1980, MNRAS, 190, 321
Laugalyas, V., & Straizys, V. 2002, Baltic Astron., 11, 205
Lennell Nemec, A. F. L., & Nemec, J. M. 1985, AJ, 90, 2317
Lobel, A., et al. 2003, ApJ, 583, 923
Malbet, F., et al. 1998, ApJ, 507, 149
McMurdie, S. 1995, Ph.D. thesis, Caltech, 72
Mendoza, E. E. 1971, ApJ, 169, L117 (erratum 172, L77 [1972])
Mould, J. R., Hall, D. N. B., Ridgway, S. T., Hintzen, P., & Aaronson, M. 1978, ApJ, 222, L123
Nakajima, T., & Golimowski, D. A. 1995, AJ, 109, 1181
Pereira, C. B., Schiavon, R. P., de Araujo, F. X., & Laudaberry, S. J. C. 2001, AJ, 121, 1071
Potok, P. D., Dzemler, R., Ilyin, I., & Tuominen, I. 1998, A&A, 331, L53
Petrov, P. P., & Herbig, G. H. 1992, ApJ, 392, 209
Petrov, P. P., et al. 2001, A&A, 369, 993
Porter, J. M. 1996, MNRAS, 280, L31
Press, W. H., Flannery, B. P., Teukolsky, S. A., & Vetterling, W. T., in Numerical Recipes, ed. W. H. Press (Cambridge Univ. Press), chap. 13, 484
Reipurth, B. 1990, in IAU Symp. 137, Flare Stars in Star Clusters, Associations, and the Solar Vicinity, ed. L. V. Mirzoyan, B. R. Petterson, & M. K. Tsvetkova (Dordrecht: Kluwer), 229
—–. 1997, poster presented at IAU Symp. 182, Low-Mass Star Formation from Infall to Outflow
Reipurth, B., Hartmann, L., Kenyon, S. J., Smette, A., & Bouchet, P. 2002, AJ, 124, 2194
Reipurth, B., Pedrosa, A., & Lago, M. T. V. T. 1996, A&AS, 120, 229
Rieke, G., Lee, T., & Coyne, G. 1972, PASP, 84, 37
Rustamov, B. N. 2001, Astron. Lett., 27, 34
Sargent, W. L. W. 1961, ApJ, 134, 142
Stellingwerf, R. F. 1978, ApJ, 224, 953
Tuominen, I., Ilyin, I., & Petrov, P. 1999, in Astrophysics with the NOT, ed. H. Karttunen & V. Vilppu (Piikkio: Univ. Turku, Tuorla Obs.), 47
Unruh, Y. C., Collier Cameron, A., & Guenther, E. 1998, MNRAS, 295, 781
Valenti, J. A., Basri, G., & Johns, C. M. 1993, AJ, 106, 2024
Wallace, L., & Hinkle, K. 1996, ApJS, 107, 312
—–1997, ApJS, 111, 445
Welty, A. D., Strom, S. E., Edwards, S., Kenyon, S. J., & Hartmann, L. W. 1992, ApJ, 397, 260
Welty, A. D., Strom, S. E., Strom, K. M., Hartmann, L. W., Kenyon, S. J., Grasdalen, G., & Stauffer, J. R. 1990, ApJ, 349, 328

We are much indebted to the late V. Shevchenko and to M. Ibrahimov for providing us with their FU/or photometry, to Keith Budge, Lee Hartmann, Ken Hinkle, and Karl Stapelfeldt for material that we have found very useful in the course of this investigation, to Ted Simon for assistance with the CO data, to Ilya Ilyin for assistance with the SOFINT observations, and to Bo Reipurth for helpful comments. The work of G. H. on FUors has been partially supported by the US National Science Foundation under grants AST 97-30934 and 02-04021. The work of P. P. and R. D. was supported by the EC Human Capital and Mobility Network project “Late-Type Stars: Activity, Magnetism, Turbulence,” and the work of P. P. was supported by the CAUP grant “Financiamiento Plurianual.”