

FLICKERING IN FU ORIONIS

SCOTT J. KENYON

Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; skenyon@cfa.harvard.edu

E. A. KOLOTILOV

Crimean Laboratory, Sternberg State Astronomical Institute, p/o Nauchny, 334413, Crimea; kolotilov@sai.crimea.ua

M. A. IBRAGIMOV

Ulugh Beg Astronomical Institute, Academy of Sciences of Uzbekistan, Astronomicheskaya ul. 33, Tashkent, 700052, Uzbekistan; mansur@astrin.uzsci.net

AND

JANET A. MATTEI

American Association of Variable Star Observers, 25 Birch Street, Cambridge, MA 02138; jmattei@aavso.org

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ABSTRACT

We analyze new and published optical photometric data of FU Orionis, an eruptive pre-main-sequence star. The outburst consists of a 5.5 mag rise at B with an e -folding timescale of ~ 50 days. The rates of decline at B and V are identical, 0.015 ± 0.001 mag yr $^{-1}$. Random fluctuations superimposed on this decline have an amplitude of 0.035 ± 0.005 mag at V and occur on timescales of 1 day or less. Correlations between V and the color indices $U-B$, $B-V$, and $V-R$ indicate that the variable source has the optical colors of a G0 supergiant. We associate this behavior with small-amplitude flickering of the inner accretion disk.

Subject headings: accretion, accretion disks — stars: formation — stars: individual (FU Orionis) — stars: pre-main-sequence

1. INTRODUCTION

FU Orionis objects—sometimes known as FUors—are eruptive pre-main-sequence stars located in active star-forming regions (Herbig 1966, 1977; Hartmann & Kenyon 1996; Kenyon 1999). Roughly half of the 11 commonly accepted FU Orionis objects have been observed to rise 3–5 mag in optical or near-IR brightness on timescales of 1–10 yr. Other FUors have been identified based on properties similar to eruptive FUors, including (1) absorption features of F–G supergiants on optical spectra and K–M giants on near-IR spectra (Herbig 1977; Mould et al. 1978; Carr, Harvey, & Lester 1987; Stocke et al. 1988; Staude & Neckel 1992); (2) large excesses of radiation over normal F–G stars at ultraviolet, infrared, submillimeter, and centimeter wavelengths (Weintraub, Sandell, & Duncan 1989, 1991; Kenyon & Hartmann 1991; Rodriguez, Hartmann, & Chavira 1990; Rodriguez & Hartmann 1992); (3) distinctive reflection nebulae (Goodrich 1987); and (4) clear association with optical jets, HH objects, and molecular outflows (Reipurth 1991; Evans et al. 1994).

FU Orionis object eruptions are often accepted as accretion events in the disk surrounding a low-mass pre-main-sequence star (Hartmann & Kenyon 1985; Lin & Papaloizou 1985; Hartmann & Kenyon 1996; for alternative interpretations, see Petrov & Herbig 1992; Petrov et al. 1998). In this picture, the accretion rate through the disk increases by 2–3 orders of magnitude to $\sim 10^{-4} M_{\odot}$ yr $^{-1}$. In addition to providing energy for the luminosity increases of FU Orionis objects, this model naturally explains the broad spectral energy distributions, the variation of rotational velocity and spectral type with wavelength, and color changes during the optical decline of V1057 Cyg, among other observed properties.

Despite the success of the disk hypothesis, one observable characteristic of disk-accreting systems—flickering—has

not been observed in any known FU Orionis object. In most systems with luminous accretion disks, flickering is observed as a series of random brightness fluctuations with amplitudes of 0.01–1.0 mag that recur on dynamical timescales (Robinson 1976; Bruch 1992). Often accepted as a “signature” of disk accretion, flickering is believed to be a dynamical variation of the energy output from the disk.¹ Thus, it provides some measure of the fluctuations in the physical structure of the disk and might someday serve as a diagnostic of physical properties within the disk (Bruch & Duschl 1993; Bruch 1994; Warner 1995).

In this paper, we search for evidence of flickering in the historical light curve of FU Ori. In addition to the outburst, we find good evidence for small-amplitude brightness fluctuations on a timescale of 1 day or less. Color changes correlated with the brightness changes indicate a variable source with the optical colors of a G0 supergiant. The amplitude, color temperature, and timescale of the variations have much in common with the flickering observed in short-period interacting binary systems. After ruling out several possible alternatives, we conclude that flickering is the most likely interpretation for short-term variability in FU Ori. The most plausible location for the flickering source is the inner edge of the disk, where temperatures lie between the stellar temperature and the maximum disk temperature of ~ 7000 K.

¹ In the cataclysmic variables (short-period binary systems with an accretion disk surrounding a white dwarf), random flickering occurs on timescales of seconds to minutes. Dwarf nova oscillations and quasi-periodic oscillations are semicoherent periodic variations observed on similar timescales. Flickering is also occasionally associated with material in the “bright spot” at the outer edge of the disk (see Warner 1995). It is unclear whether or not these classes have distinct analogs among accreting pre-main-sequence stars. In this paper, we use flickering to distinguish rapid variations of light from the inner disk from variations of the bright spot.

TABLE 1
OPTICAL PHOTOMETRY

Julian Date (2,400,000 +)	<i>V</i>	<i>B</i> − <i>V</i>	<i>U</i> − <i>B</i>
46,320.581	9.28	1.34	...
46,325.582	9.27
46,328.589	9.27	1.33	...
46,357.619	9.24	1.32	0.92
46,378.610	9.31
46,405.534	9.32	1.31	0.96
46,406.543	9.33	1.29	0.88
46,407.528	9.28	1.28	...
46,466.342	9.31	1.32	0.92
46,703.561	9.25	1.36	1.02
46,710.579	9.27	1.34	0.95
46,761.514	9.26	1.30	0.90
46,773.390	9.21	1.34	0.95
46,774.419	9.23	1.33	0.99
46,831.314	9.30	1.32	0.92
46,852.272	9.31	1.33	1.00
46,855.217	9.32	1.33	1.04
47,183.313	9.17	1.36	...
47,184.308	9.24	1.36	1.02
47,202.361	9.29	1.34	0.96
47,205.233	9.28	1.35	0.99
47,207.319	9.27	1.33	...
47,208.338	9.29	1.35	0.95
47,569.377	9.32	1.32	0.88
47,861.478	9.42	1.40	0.93
47,920.262	9.39	1.30	0.87
47,967.240	9.38	1.33	0.88
47,971.227	9.42	1.29	0.87
48,159.561	9.45	1.28	0.88
48,273.356	9.42	1.29	0.90
48,325.318	9.46	1.28	0.90
48,540.557	9.45	1.27	0.92
49,780.219	9.44	1.29	0.93
50,156.258	9.45	1.30	0.91
50,509.243	9.54	1.29	0.92
50,863.205	9.57	1.26	0.89

We describe the observations in § 2, analyze the light curve in § 3, and conclude with a brief discussion and summary in § 4.

2. OBSERVATIONS

We acquired *UBV* photometry of FU Ori with the 60 cm Zeiss reflector at the Crimean Laboratory of the Sternberg State Astronomical Institute. The observations usually were made through a 13" aperture; a 27" aperture was used on nights of poor seeing. These data were reduced using BD

TABLE 2
ABSORPTION INDICES

Julian Date	CH	H β	Mg I	Na I	TiO ₁	TiO ₂
2,446,722	0.34	0.15	0.07	0.24	−0.01	−0.02
2,447,106	0.23	0.19	0.06	0.23
2,447,496	0.19	0.16	0.08	0.21
2,448,404	0.21	0.21	0.14	0.23	−0.04	−0.02
2,449,836	0.33	0.20	0.16	0.26	−0.03	−0.06
2,450,781	0.28	0.22	0.15	0.29	−0.01	−0.06
2,450,983	0.31	0.20	0.19	0.29	−0.02	−0.07
2,451,010	0.31	0.20	0.20	0.29	−0.02	−0.09
2,451,026	0.30	0.24	0.19	0.30	−0.03	−0.08

+8°1051 as the comparison star and other nearby stars as controls (see Kolotilov & Petrov 1985). Table 1 lists the results. The uncertainty in the calibration is ± 0.01 – 0.02 mag for *V* and *B* − *V* and ± 0.02 – 0.04 mag for *U* − *B*.

We supplement the *UBV* data with additional photoelectric photometry from the Maidanak High Altitude Observatory. Ibragimov (1997) describes *UBVR* data acquired during 1981–1994 as part of the ROTOR project. The data have been reduced to the standard *UBVR* system with typical errors of ± 0.015 mag for *V* and *V* − *R*, ± 0.02 mag for *B* − *V*, and ± 0.04 – 0.08 mag for *U* − *B*.

We also consider visual observations of FU Ori compiled by the American Association of Variable Star Observers (AAVSO). The error of a typical estimate is 0.1–0.2 mag using standard stars in the field of FU Ori calibrated from photoelectric observations. We simplify a comparison with photoelectric data by computing 20 day means of the over 7000 AAVSO observations. With ~ 15 observations per 20 day interval, this procedure reduces the typical error of a 20 day mean to ~ 0.03 mag, only slightly larger than the quoted error of the photoelectric data.

Finally, we obtained low-resolution optical spectra of FU Ori during 1995–1998 with FAST, a high-throughput, slit spectrograph mounted at the Fred L. Whipple Observatory 1.5 m telescope on Mount Hopkins, Arizona (Fabricant et al. 1998). We used a 300 grooves mm^{−1} grating blazed at 4750 Å and a 3" slit and recorded the spectra on a thinned Loral 512 × 2688 CCD. These spectra cover 3800–7500 Å at a resolution of ~ 6 Å. On photometric nights, we acquired standard star observations to reduce the FU Ori data to the Hayes & Latham (1975) flux scale using NOAO IRAF.² These calibrations have an accuracy of ± 0.05 mag. This uncertainty is comparable to the probable error in spectrophotometric data acquired with the Kitt Peak National Observatory Intensified Reticon Spectrograph reported in Kenyon, Hartmann, & Hewett (1988).

Table 2 lists indices for several absorption lines using O’Connell’s (1973) definition, $I_\lambda = F_\lambda/\bar{F}_\lambda$, where F_λ is the measured flux in a 20 Å bandpass centered at wavelength λ and \bar{F}_λ is the continuum flux interpolated from continuum bandpasses on either side of the absorption feature. Repeat measurements indicate an error of ± 0.03 mag for each index.

3. LIGHT CURVE ANALYSIS

The lower panel of Figure 1 shows historical *B* + photographic and optical light curves for FU Ori. Following a 5–6 mag rise at *B*, the system has declined by ~ 1 mag in nearly 70 yr. The decline in visual light has closely followed the *B* light curve for the past 30 yr. In addition to a long-term wavelike variation, the brightness shows considerable scatter of roughly 0.1 mag at *BVR* and almost 0.2 mag in *U* on timescales of days to months. These fluctuations are much larger than the quoted photometric errors. Ibragimov (1997) commented on fluctuations in brightness and color indices throughout 1981–1994. Similar variations are visible in light curves of V1057 Cyg and V1515 Cyg (Ibragimov 1997). We plan analyses of these other FU Orionis objects in future publications.

² IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.

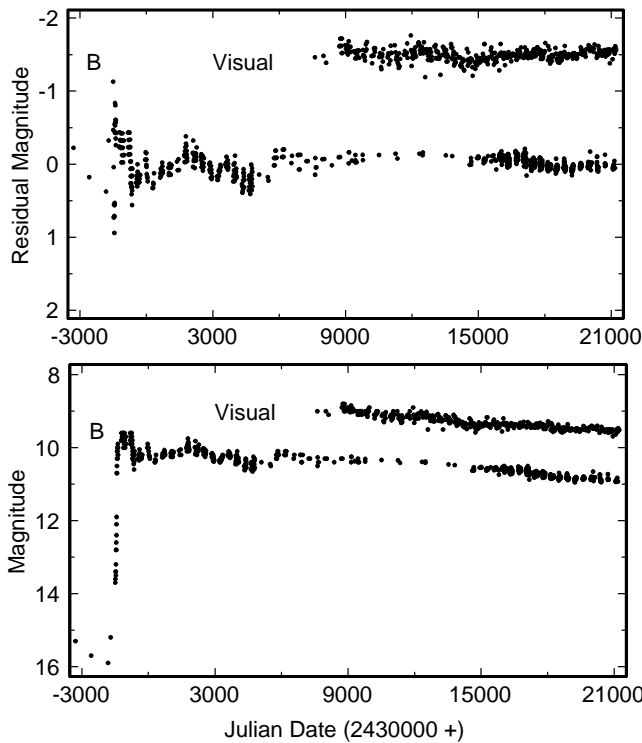


FIG. 1.—Residual (*upper panel*) and optical (*lower panel*) light curves for FU Ori. The blue (*B*) light curve is composed of 1042 measurements derived from photographic plates and photoelectric photometry (Ibragimov 1997 and references therein). The visual light curve is 20 day means of 7300 visual observations from the AAVSO international database. The residuals plot the difference between the *B* and visual light curves in the lower panel and the model light curves described in the text. Both residual light curves show large, short-timescale fluctuations superimposed on a wavelike variation with a timescale of 3000–3500 days.

3.1. Outburst Model

To analyze brightness fluctuations in FU Ori, we begin by separating long-term changes with timescales of years from shorter timescale variations. We consider a simple model for the outburst,

$$m = m_0 + m_{\text{rise}}(t - t_0), \quad (1)$$

where m_0 is the average quiescent magnitude and t_0 is the time of the outburst. The brightness during outburst is a function of time, t ,

$$m_{\text{rise}} = \begin{cases} 0 & t < t_0, \\ \delta m_{\text{rise}}[1 - e^{-(t-t_0)/\tau_{\text{rise}}}] + \dot{m}(t - t_0) & t \geq t_0, \end{cases} \quad (2)$$

where δm_{rise} is the amplitude of the outburst, τ_{rise} is the e -folding time of the rise to maximum, and \dot{m} is the rate of decline from maximum. We derive parameters for this model using a downhill simplex method to minimize the function

$$\chi^2 = \sum_{i=1}^N [(m - m_i)/\sigma_i]^2 \quad (3)$$

for N observations m_i having uncertainty σ_i . We derive the model parameters m_0 , δm_{rise} , \dot{m} , and τ_{rise} for an adopted t_0 and vary t_0 separately to produce a minimum in χ^2 . This procedure works better than fitting all parameters at once because of the sparse nature of the light curve for $t \lesssim t_0$. To estimate errors of the model parameters, we compute

residuals r_i of the light curve about the fit, construct new light curves by adding Gaussian noise with amplitude r_i to the data, and extract new model parameters. We adopt as best the median values for model parameters from 10,000 such trials; the quoted errors are the interquartile ranges of each model parameter.

Table 3 summarizes results of model fits to the light curves in Figure 1. The sparse data before outburst yield a poor measure of the preoutburst brightness and the start of the outburst. We estimate $t_0 = \text{JD } 2,428,497 \pm 40$ and $m_0 = 15.55 \pm 0.40$ from the *B*-band data; these errors set the uncertainties in the other model parameters. The uncertainty in the decline rate at *B* is small; the visual data yield a nearly identical rate of decline despite lack of data near maximum.

The spectroscopic data show little evidence for any change in the mean optical spectral type during the recent 0.3 mag decline in the mean *V* brightness. The Mg I $\lambda 5175$ index, which tracks the spectral type rather well, increased by at most 0.02 mag during these years. The H β and Na I $\lambda 5893$ indices, which should measure the wind of FU Ori, have also remained constant. We show below that the mean colors, $U - B$, $B - V$, and $V - R$, of FU Ori have changed by $\lesssim 0.02$ mag in 15 yr. The constant colors and spectral indices indicate that the optical spectral type has remained constant to within ± 1 subclass since 1985.

The upper panel of Figure 1 shows residual light curves about the best-fit model. The rms dispersion about the light curves is 0.06 mag for photoelectric data, 0.11 mag for visual data, and 0.24 mag for photographic data. All are large compared to typical uncertainties.

Some of the scatter in the residual light curves is due to a long-term wave with an amplitude of several tenths of a magnitude. The residual *B* light curve has three prominent crests at $\sim \text{JD } 2,428,500$, $\text{JD } 2,432,000$, and $\text{JD } 2,436,000$, with a possible small crest at $\sim \text{JD } 2,433,500$. This behavior appears to vanish in the *B* light curve at later times. However, the residual visual light curve then shows a similar wavelike oscillation with crests at $\sim \text{JD } 2,439,000$ and $\text{JD } 2,442,500$. Another crest at $\sim \text{JD } 2,447,000$ is present in the photoelectric *V* light curve shown in Figure 2 and described below. These peaks are roughly in phase with the residual *B* light curve for periods of ~ 4000 days.

There are considerable photometric variations in addition to the wave. These occur on short timescales, tens of days or less, and have amplitudes that seem uncorrelated with the overall system brightness. We will analyze these in the next section and then consider possible origins for the short-term and long-term variations.

Despite the large residuals, the model fits leave negligible trends in the data. The median Spearman rank correlation coefficient between the *V* brightness and time for the 10,000 Monte Carlo trials is 0.87 for the *B*+photographic data and 0.84 for the visual data. The median slope of a linear fit

TABLE 3
LIGHT-CURVE PARAMETERS

Parameter	<i>B</i> + pg	Visual
m_0 (mag)	15.55 ± 0.40	...
δm_{rise} (mag)	5.5 ± 0.4	...
τ_{rise} (days)	52 ± 25	...
\dot{m} (mag yr $^{-1}$)	0.0140 ± 0.0015	0.0166 ± 0.0012

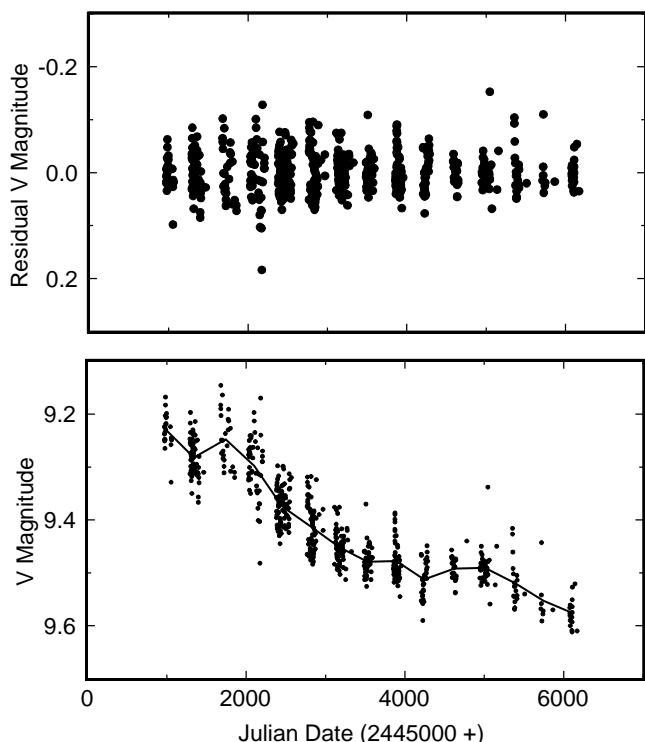


FIG. 2.—Photoelectric V -band data for FU Ori. *Bottom panel*: filled circles indicate individual data points; the solid line shows seasonal means. *Top panel*: variation of individual data points about the seasonal mean light curve.

to the residual light curves is $\lesssim 10^{-4}$ mag yr $^{-1}$ for the B + photographic data and $\lesssim 10^{-6}$ mag yr $^{-1}$ for the visual data. We conclude that the simple model provides a reasonable fit to the long-term light curve and now consider the nature of the shorter timescale fluctuations.

3.2. Fluctuation Timescale

To test whether or not the short timescale photometric variations in FU Ori are flickering, we need to verify that (1) they are real changes in the brightness and color of FU Ori, (2) they occur on short timescales but are not periodic, and (3) they can be plausibly associated with radiation from the disk. We establish the reality of the variations in two parts. We first demonstrate that the variations occur on short timescales with amplitudes larger than the photometric errors. We show later that color changes correlate with brightness changes.

We consider a Monte Carlo model for the photoelectric data described in § 2. The lower panel of Figure 2 shows V -band data acquired during the last 15 yr. Both the wavelike oscillation and the large scatter about this oscillation are apparent. The solid line in this figure is the seasonal mean light curve, the average brightness for each year of observation. The top panel in the figure is the difference between the actual data and the seasonal mean. This residual light curve has a large amplitude but no linear trend or wavelike feature.

Our analysis indicates a small periodic component in residual light curves for B and V data. Periodograms suggest a period of 17 ± 1 days in the B data, which has been reported previously (Kolotilov & Petrov 1985). This periodic component has an amplitude of 0.009 ± 0.003

mag. The V data has a best period of 111.4 ± 1.6 days with an amplitude of 0.012 ± 0.003 mag. There is no indication of the 17 day period in the V light curve. The amplitudes of these “periodicities” are comparable to the photometric errors but small compared to the amplitude of the fluctuations in the residual light curves (see Figs. 1 and 2).

To measure the amplitude of the nonperiodic component in the residual light curve, we use a Monte Carlo model. We replace each observation V_i with a random brightness having amplitude a_v and offset v_0 ,

$$v_i = v_0 + a_v g_i, \quad (4)$$

where g_i is a normally distributed deviate with zero mean and unit variance (Press et al. 1992). Artificial light curves that provide a good match to the actual light curve should have the same amplitude and offset. We quantify a “good match” by comparing the magnitude distributions of actual and artificial light curves using the Kolmogorov-Smirnov (K-S) test. We reject poor matches with a low probability of being drawn randomly from the same distribution as the data. The “best” match maximizes the median K-S probability from 10,000 trials. We establish error estimates for the best parameters and the proper scale for this measure by comparing two artificial light curves generated in each of 10,000 trials.

This procedure yields best parameters of $v_0 = 0.0016 \pm 0.0009$ mag and $a_v = 0.033 \pm 0.005$ mag for the residual V light curve. Artificial light curves with these parameters have a high probability, 68% or larger, of being drawn randomly from the same distribution as the actual data. The offset of the model light curve is consistent with zero. The amplitude of the model is roughly twice the quoted 1σ error of 0.015 mag.

The artificial data sets have periodic variations similar to the real data sets. Periods of 10–100 days are common in the artificial B and V light curves. Mean light curves folded on these periods have amplitudes, 0.01 ± 0.003 mag, similar to those quoted above for the real data. The “best” period is different in each artificial data set, but the amplitude is nearly constant. This amplitude is small compared to the random component of the fluctuation. We suspect the periodic variations are due to the sampling of the light curve. Such “periodicities” illustrate some of the dangers of period analysis.

There are two explanations for the 0.03 mag variations in the residual V light curve. A simple test should distinguish real fluctuations from measurement error. Real fluctuations in V should be accompanied by correlated variations in the color indices, $U-B$, $B-V$, and $V-R$. Color variations should be uncorrelated with the V brightness and with each other if the measurement error is 0.03 mag in V instead of 0.015 mag. In either case, the Monte Carlo model demonstrates that the fluctuations occur on short timescales. The typical observation frequency is ~ 1 day $^{-1}$ (344 out of 663 observations), 0.5 day $^{-1}$ (82 observations), or 0.333 day $^{-1}$ (54 observations). Fluctuations must occur on timescales $\lesssim 1$ day based on the success of the Monte Carlo model in reproducing the light curve.

3.3. Color Variations

Figure 3 shows the variations in the optical colors as a function of time. The solid line in each of the left-hand panels is the seasonal mean color for the individual data points. There is little evidence for a substantial color change

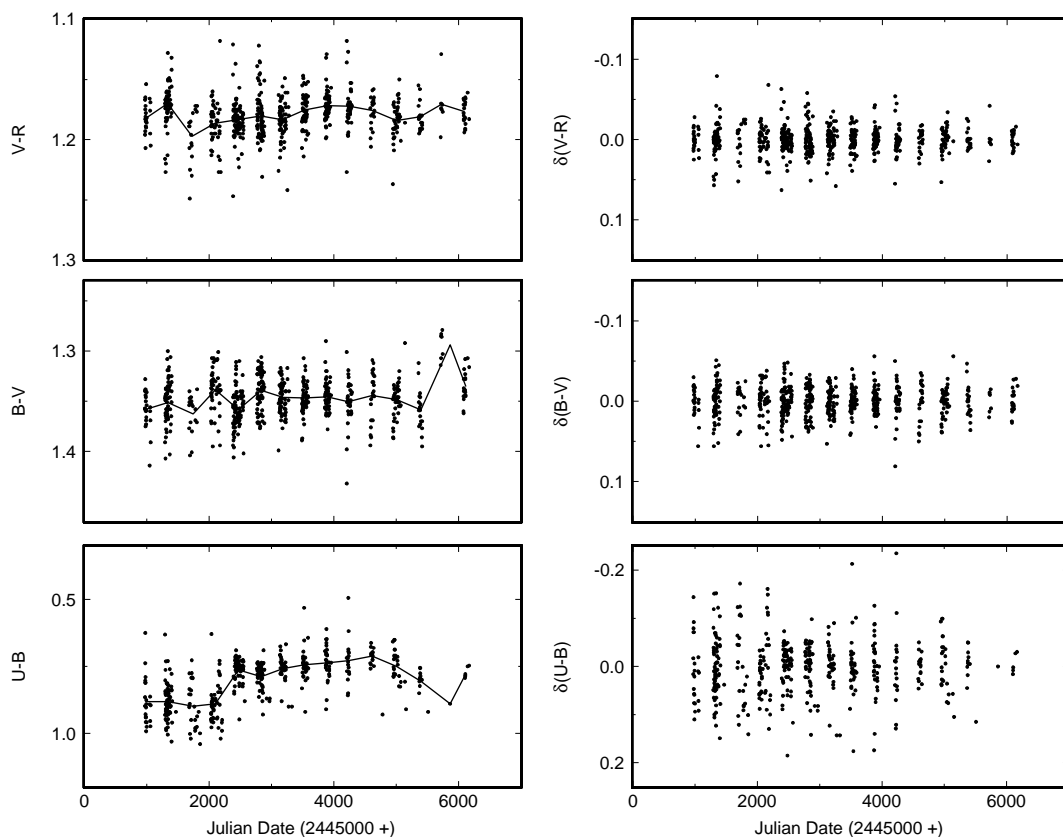


FIG. 3.—Color variations in FU Ori. In each panel on the left, filled circles indicate individual data points; the solid line shows seasonal means. Filled circles in the right-hand panels indicate the variation of each color about the seasonal mean color curves in the left-hand panels.

in FU Ori during a 0.3 mag decline in V . The seasonal means for $B-V$ and $V-R$ are constant to within the photometric errors. The variation in the mean $U-B$ color is roughly twice the photometric error but shows no obvious trend with time.

Despite the lack of long-term variation in the colors, there are considerable short-term variations. The right-hand panels in Figure 4 show the color fluctuations about the seasonal means in the left-hand panels. The full amplitudes of the color variations are ~ 0.2 mag in $U-B$ and ~ 0.1 mag in $B-V$ and $V-R$. These variations are 3–5 times the quoted photometric errors.

Figures 4–5 show the correlation of color variations with the V -band fluctuations analyzed in § 3.2. To construct these plots, we derived separate seasonal means for the V -band observations associated with each color observation (because a given color was not always obtained with each V measurement) and subtracted the appropriate seasonal mean from each data point. The Spearman rank correlation coefficient is 1.3×10^{-2} for 438 $\delta(U-B)$ - δV pairs, 2.6×10^{-9} for 626 $\delta(B-V)$ - δV pairs, and 2.9×10^{-11} for 622 $\delta(V-R)$ - δV pairs. We fit each correlation with a straight line using the Press et al. (1992) subroutine FITEXY, assuming that the 1σ errors in each coordinate are equal to the quoted photometric errors. The results yield

$$\delta(U-B) = -0.0002 \pm 0.0034 - (0.40 \pm 0.14)\delta V, \quad (5)$$

$$\begin{aligned} \delta(B-V) &= (-0.24 \pm 8.0) \times 10^{-4} \\ &\quad - (0.12 \pm 0.02)\delta V, \end{aligned} \quad (6)$$

$$\begin{aligned} \delta(V-R) &= (-0.015 \pm 6.1) \times 10^{-4} \\ &\quad + (0.15 \pm 0.02)\delta V. \end{aligned} \quad (7)$$

The correlation between $\delta(U-B)$ and δV is weak; $U-B$ becomes redder as the source becomes brighter. Both

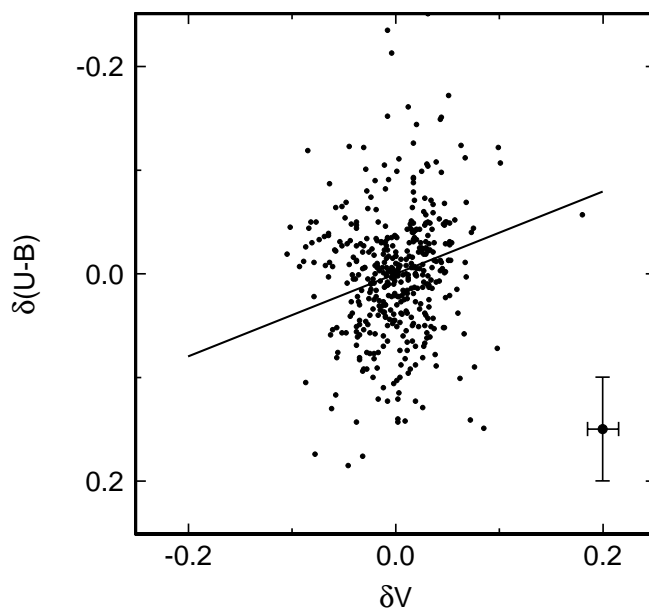


FIG. 4.—Correlation of $U-B$ variations with V -band variations. The straight line is a least-squares fit to the plotted points. The error bar in the lower right corner indicates the uncertainty of a single observation.

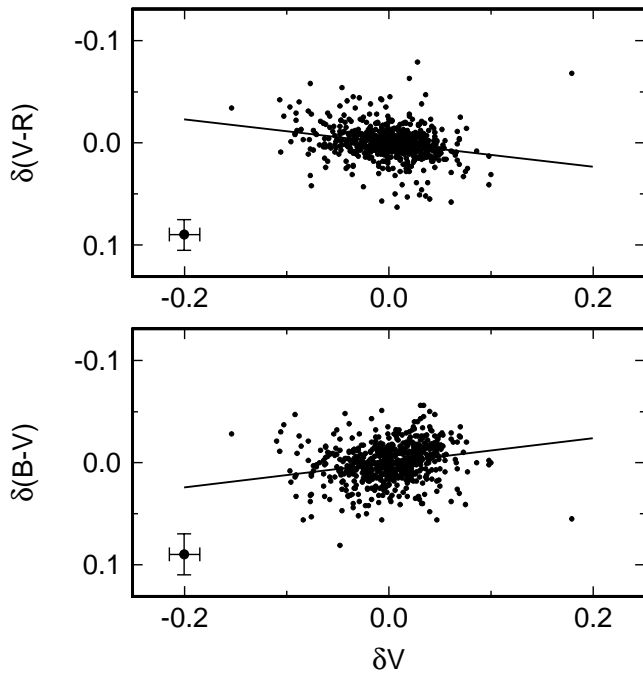


FIG. 5.—Correlation of color variations with V -band variations. The lower panel plots the variation of $B-V$ with V ; the upper panel plots the variation of $V-R$ with V . In each panel, the straight line is a least-squares fit to the plotted points. The error bars indicate the uncertainty of a single observation.

$\delta(B-V)$ and $\delta(V-R)$ correlate well with δV ; as the source brightens, $B-V$ becomes redder while $V-R$ becomes bluer.

The slopes of the short-term color variations in equations (5)–(7) differ from the apparent slope of the long-period wave in the B and visual light curves. The lack of a clear B variation associated with the visual wave suggests $\delta(B-V) \approx C\delta V$, with $C \approx 1$. This behavior suggests that the wave and the short-term fluctuations have different physical origins. Analysis of photoelectric data with a longer time baseline is needed to verify this point.

To test the accuracy of the correlation coefficients and measured slopes, we constructed artificial color curves using the Monte Carlo model described in § 3.2. We matched model color curves having amplitudes similar to the observations to model V -band light curves, measured the correlation coefficients, and derived the slopes of straight-line fits to the artificial residuals. We repeated this exercise using known correlations of color index with brightness. Random light curves yield no correlation between color index and brightness. Correlated changes in color index with brightness yield the measured correlation coefficients if the amplitude of the brightness variation is $a_v = 0.036 \pm 0.007$, if the slopes and 1σ errors of the color variations are those quoted in equations (5)–(7), and if the photometric errors are 0.015 ± 0.01 in V , 0.02 ± 0.01 in $B-V$ and $V-R$, and 0.07 ± 0.02 in $U-B$.

The small color variations make it difficult to find robust correlations among the color indices. There is a 3σ correlation between $U-B$ and $B-V$, with a Spearman rank coefficient of 4.7×10^{-3} . The Spearman rank correlation coefficient is much larger, 0.25, for $B-V$ and $V-R$. To test the importance of these results, we repeated these tests using artificial data sets with known correlations between the

color indices. The correlation between $\delta(U-B)$ and $\delta(B-V)$ is always detected in data with small photometric errors; the Spearman rank correlation coefficient is 10^{-3} or smaller in all of our trials. The correlation between $\delta(B-V)$ and $\delta(V-R)$ has 2σ or smaller significance in all of our trials. Reducing the photometric errors by factors of 2–3 allows us to recover known correlations at the 3σ level.

These results provide good evidence that the observed variations in brightness and color are intrinsic to FU Ori. The correlations between the $B-V$ or $V-R$ color and the V brightness are robust. The measured correlation coefficients are reasonable given the magnitude of the color changes and the photometric errors. We next consider the physical nature of the brightness changes and then compare these properties with the flickering observed in other accreting systems.

3.4. Physical Nature of Light and Color Variations

The observed optical light and color variations in FU Ori are small, ~ 0.035 mag in V , ~ 0.015 mag in $U-B$, and ~ 0.004 mag in $B-V$ and $V-R$. To understand the origin of this variability, we consider the observed colors as small perturbations about the colors of the “average” source in FU Ori. We adopt the mean colors of the system as the average colors,

$$U-B = 0.84, \quad B-V = 1.35, \quad V-R = 1.15, \quad (8)$$

and correct these colors for interstellar reddening assuming a standard extinction law (Mathis 1990) and $A_V = 2.2$ mag (Kenyon et al. 1988),

$$(U-B)_0 = 0.33, \quad (B-V)_0 = 0.64, \\ (V-R)_0 = 0.60. \quad (9)$$

Figure 6 compares the reddening-corrected color indices of FU Ori with colors for F and G supergiants as indicated in the plot. The average colors of FU Ori, shown as the box, are offset from standard stellar loci. The solid line in each panel shows how the colors change as the source brightens; the colors move away from the supergiant locus if the source fades in brightness. Both lines indicate that the best stellar match to the changes in brightness and color is a G0 supergiant. The dashed lines indicate how the colors change if the slopes of the relation between the V -band brightness and the color indices are $\pm 2\sigma$ different from those derived in equations (5)–(7). This result shows that the uncertainty in the stellar match is less than 1 spectral subclass.

The best stellar match to the color variations is correlated with the adopted reddening. An F5 supergiant can match the observed color variations for $A_V = 3.2$ mag; a G5 supergiant is the best match for $A_V = 1.2$ mag. Intrinsic colors for $A_V \lesssim 1.5$ mag and $A_V \gtrsim 3$ mag are inconsistent with the G-type optical spectrum. This constraint limits the spectral type of the variable source to F7–G3.

To find a reasonable explanation for the color variations, we first consider mechanisms appropriate for single stars without circumstellar disks. Although we believe an accretion disk provides the best model for observations of all FU Orionis objects, it is important to consider alternatives before we identify flickering as the source of the variability in FU Ori. Obscuration, pulsation, and rotation are obvious choices for short-period variations with small amplitudes in an isolated star. Random obscuration events by small, intervening dust clouds near the central source are

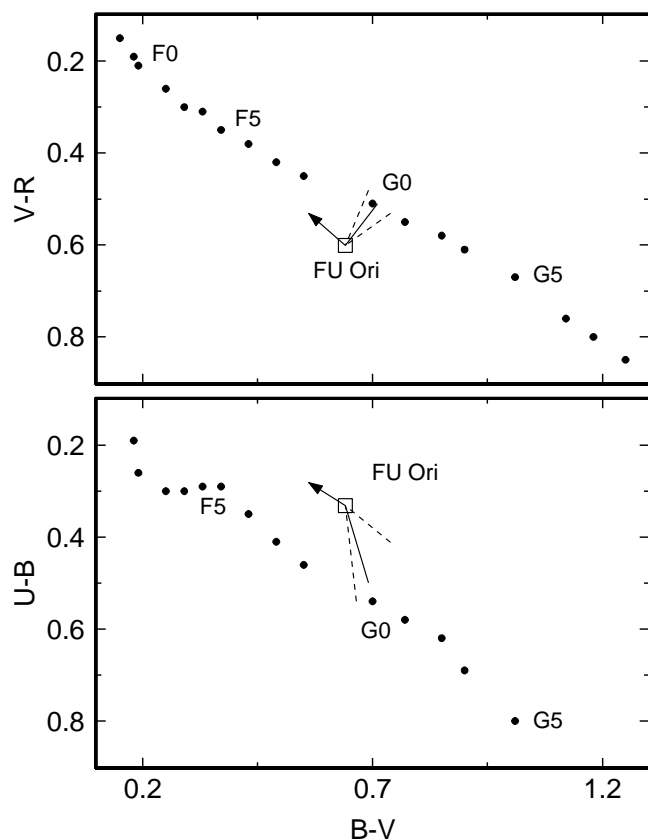


FIG. 6.—Flux ratio diagrams for FU Ori. In each panel, a box shows the reddening-corrected position of FU Ori, filled circles show positions of F–G supergiants with indicated spectral types, the solid line points to the best stellar match to the colors of the variable source, and the dashed lines show $\pm 2\sigma$ uncertainties in the best stellar match. A G0 supergiant provides the best match to the observed color variations with an uncertainty of roughly 1 spectral subclass.

a popular model for rapid variations in Herbig Ae/Be stars and other pre-main-sequence stars (e.g., Natta et al. 1997; Rostopchina et al. 1997 and references therein). The observed pulsational amplitude of the pre-main-sequence star HR 5999, 0.013 mag (Kurtz & Marang 1995), is close to the amplitude observed in FU Ori. The period of 5 hr is short compared to the spacing of our data; a similar period in FU Ori might well be missed by an analysis described above. Rotational modulations with small amplitudes and periods of 1–2 days are observed in many pre-main-sequence stars (Kearns et al. 1997 and references therein) and could plausibly produce a similar variation in FU Ori.

Despite its attractiveness, a stellar pulsation in FU Ori seems unlikely. With an effective temperature of ~ 6000 – 6500 K and a luminosity of $\sim 200 L_{\odot}$ (e.g., Kenyon 1999), FU Ori lies within the classical instability strip (see Gautschy & Saio 1995). The bright Cepheid α UMi (Polaris) has a comparable amplitude and other Cepheids have similar periods. Recent period-luminosity relations for Cepheids (Feast & Catchpole 1997; Hindsley & Bell 1989) yield periods of ~ 0.8 days for FU Ori if $d = 500$ pc and $A_V = 2.2$ mag. Although this period is reasonably consistent with our observations, FU Ori lies well above the *pre-main-sequence* instability strip in the HR diagram (Marconi & Palla 1998). To test the possibility that a pulsational instability might occur anyway, we constructed artificial

light curves with amplitudes of 0.035 mag and periods of 0.3–2.0 days. We sampled these light curves in time as in our real observations and added noise equivalent to our photometric uncertainties. Our failure rate for recovering known periods in the artificial light curves is small, $\lesssim 10^{-3}$, for all periods considered, based on 10,000 artificial light curves at each of 20 periods between 0.3 and 2.0 days. The failure rate is largest for periods of 0.5, 1.0, and 1.5 days due to the ~ 1 day spacing of the light curve. The failure rate decreases to 10^{-4} or less at other periods. Our inability to detect any periodicity in the FU Ori light curve and the lack of a theoretical instability strip for the observed luminosity and temperature of FU Ori is a strong indication that pulsations do not produce the observed variation.

Stellar rotation is also an unlikely source of the variability. The light curve analysis for short periodicities rules out a rotational modulation of the light curve, unless the dark or bright spots responsible for the variations vary in size or intensity on timescales of several rotational periods. At the 1–2 day periods that seem most plausible, FU Ori currently rotates close to breakup. If the star conserved angular momentum during the rise to maximum, the preoutburst rotational velocity would have exceeded the breakup velocity by a factor of ~ 3 (see also Hartmann & Kenyon 1985).

Obscuration events similar to those envisioned in Herbig Ae/Be stars (see Rostopchina et al. 1997 and references therein) require special circumstances to explain the variability. Reddening by small dust clouds requires unusual particles to account for a very steep reddening law, $R_V \sim 8$, that changes sign at V . Light scattered off a reflection nebula might account for the different color variations of $B-V$ and $V-R$, but it is difficult to derive as steep a color variation as is observed with simple geometries and a wide range of dust properties. Photopolarimetry would test this conclusion.

Finally, fluctuations in the wind of FU Ori are a less plausible source of brightness changes than flickering. Errico et al. (1997) have suggested that the continuum optical depth through the wind exceeds unity in the Balmer and Paschen continua. Small variations in the optical depth due to inhomogeneities in the outflow might account for small brightness changes. If correct, this hypothesis would predict a decrease in the amplitude of the variation with decreasing wavelength because the optical depth in the Paschen continuum decreases with decreasing wavelength. For reasonable wind temperatures and densities, ~ 5000 – $10,000$ K and $\sim 10^{10}$ – 10^{14} cm $^{-3}$ (Calvet, Hartmann, & Kenyon 1993; Hartmann & Calvet 1995), the increase in the optical depth from B to R is roughly a factor of 3 for a gas in LTE. There is no evidence for this behavior in FU Ori.

We conclude that fluctuations associated with a stellar photosphere or wind from the disk provide a poor explanation for the rapid, small-amplitude photometric variations in FU Ori. The variations in FU Ori have much in common, however, with the flickering observed in other accreting systems, such as cataclysmic variables (CVs) and low-mass X-ray binary systems (Bruch 1992, 1994; Bruch & Duschl 1993; Warner 1995 and references therein). In most CVs, 0.01–1 mag fluctuations occur on the dynamical time-scale, seconds to minutes, of the inner disk. Within each flicker, a CV becomes bluer as it gets brighter. The large color temperature, $\gtrsim 20,000$ K, of the variable source also plausibly confines the flickering to the inner disk in many CVs. Despite the lack of a good physical model for flicker-

ing in CVs, it clearly probes physical conditions in the inner disk.

The observed variations of FU Ori are also plausibly associated with the inner regions of a circumstellar accretion disk. The timescale of the variation, $\lesssim 1$ day, is close to the dynamical timescale of the inner disk, ~ 0.1 day for a $1 M_{\odot}$ central star with a radius of $4 R_{\odot}$. The temperature of the variable source, ~ 6000 K for a G0 supergiant, is comparable to the inner disk temperature of 6500 K derived from detailed fits to the spectral energy distribution and the profiles of various absorption lines (Kenyon et al. 1988; Bell et al. 1995; Turner, Bodenheimer, & Bell 1997). Finally, the amplitude of the variation is similar to that observed in other accreting systems. Given this behavior, we believe that the variations in FU Ori are flickering and thus provide additional evidence for an accretion disk in this system.

The main alternative to a variable accretion disk in FU Ori is variations associated with a magnetic accretion column. Despite the success of this model in other pre-main-sequence stars (e.g., Gullbring et al. 1996), truncating an accretion disk with the large accretion rate, $\sim 10^{-4} M_{\odot} \text{ yr}^{-1}$, estimated in FU Ori requires a large magnetic field, ~ 10 kG. Limits on the magnetic fields of other pre-main-sequence stars are much smaller, $\lesssim 2\text{--}3$ kG (Johns-Krull, Valenti, & Koresko 1999). A much larger field in FU Ori is unlikely. The temperature of the variable source in FU Ori, ~ 6000 K, also seems too cool to be associated with a magnetic accretion column, where the typical temperature is $\sim 10^4$ K (e.g., Lamzin 1998; Calvet & Gullbring 1998). Both of these arguments make a stronger case for flickering as the source of the variability in FU Ori.

To see what we can learn about the inner disk from the variations, we consider several simple models for the flickering. We adopt the observed colors ($U-B$, $B-V$, and $V-R$) as the colors of the average state of the disk. We assume several sources of variability in a steady state disk: (1) discrete changes in the mass accretion rate \dot{M} through the entire disk, (2) random fluctuations in the flux from any annulus in the disk, and (3) random fluctuations in the flux from specific annuli in the disk. We chose a steady state disk as the average source because steady disks provide a reasonable fit to the complete spectral energy distribution of FU Ori. Several experiments with nonsteady disks yield similar results.

Models where the entire disk can vary in brightness do not reproduce the observations. We assume a disk composed of discrete annuli with width δR at a distance R from the central star, with $\delta R \ll R$. Each annulus radiates as a star with the effective temperature assigned to the annulus. The arrows in Figure 6 indicate the color variations produced by models where the flux from each annulus is a random fraction, between 1.0 and 1.1, of the flux from the annulus of a steady state disk. The color variation of the model clearly fails to account for the observed color variation. Allowing all annuli to vary coherently also produces color variations that disagree with the observed variation.

Successful models allow only specific parts of the disk to vary in brightness. If disk annuli with the colors of F9–G1 supergiants are the only annuli that vary, the color variation of the model follows the slope of the observed variation.

Our results for flickering in FU Ori are at odds with predictions of the simple steady state accretion disk model.

In steady disk models for FU Orionis objects, the disk temperature rises rapidly from zero at the stellar photosphere, $R = R_*$, to $T_{\text{max}} \approx 6500\text{--}7000$ K at $R = 1.36 R_*$ and then decreases radially outward (Kenyon et al. 1988). The G0 temperature of the flickering source has a temperature of ~ 6000 K. Disk material with this temperature has $R = 2.5 R_*$ in the steady model. Fluctuations in the energy output of this region, and the lack of fluctuations in hotter disk material, seem unlikely. If we associate flickering with small changes in the mass accretion rate through the disk, \dot{M} , or in the scale height of the disk, H , we expect these to produce larger variations at smaller disk radii.

Recent calculations indicate that the inner regions of the disks of FU Orionis objects may be much different than predicted by the simple disk model. The steady state temperature distribution assumes a physically thin disk, $H \ll R$ (Lynden-Bell & Pringle 1974). FU Orionis object disks are probably much thicker (Lin & Papaloizou 1985; Clarke, Lin, & Papaloizou 1989; Clarke, Lin, & Pringle 1990). Steady models that include a self-consistent treatment of the boundary layer between the inner disk and the stellar photosphere predict large scale heights, $H/R \sim 0.1\text{--}0.3$ at $R \sim 1\text{--}2 R_*$ (Popham et al. 1993, 1996). Time-dependent models further indicate that H/R can vary in a complicated way close to the central star (Turner et al. 1997; Kley & Lin 1999). Both types of model predict that the disk temperature peaks just outside the stellar photosphere at $R \approx 1.1\text{--}1.2 R_*$. The decline in disk temperature at smaller radii can be as large as 25%–50%. Applied to FU Ori, these models predict that the disk temperature close to the central star is $\sim 5000\text{--}6000$ K, comparable to the temperature derived for the flickering source, if the peak temperature at $1.1\text{--}1.2 R_*$ is ~ 7000 K.

We propose that the flickering source in FU Ori lies between the stellar photosphere and the peak temperature in the disk at $1.1\text{--}1.2 R_*$. In the models described above, this region produces $\sim 5\%$ of the total optical light. Observable variations in the total light from the disk—as we have reported here—thus imply significant changes in the physical structure of the inner disk. Our data for FU Ori require 50% variations in the light output of the inner disk.

Large changes in the physical structure of the disk can be avoided if the spatially thick portion of the disk occults the inner disk. If we view the disk at an inclination $i_{\text{crit}} = \tan^{-1}(H/R)$, small variations in H/R can produce small changes in brightness and color. Rapid variations similar to those observed are possible if H/R varies on the dynamical timescale and if the occulted portion of the disk radiates as a G0 I star. The required change in H/R , $\sim 10\%$, is small compared to the 50% change in light output needed above. The required geometry is, however, very special and yields no variation if the real viewing angle is much less than i_{crit} . Observations of V1057 Cyg and V1515 Cyg will test this idea because these systems probably have smaller i than FU Ori (Hartmann & Kenyon 1996).

4. DISCUSSION AND SUMMARY

Our results provide the first evidence for rapid photometric variations—flickering—in a FU Orionis object. The amplitude of the variation is small, ~ 0.035 , and just detectable with photoelectric data covering a long time interval. Observations with smaller photometric uncertainties are needed to verify the detection and to place better limits on the color variations. Differential photometry using a CCD

on a small telescope can achieve the required precision, but the field of FU Ori has few bright comparison stars within 15° – 20° . The richness of the field may compensate and allow the high-quality photometry needed to improve our results.

Previous attempts to find similar short-term variations in a pre-main-sequence star have met with mixed success. Smith, Jones, & Clarke (1996) placed upper limits of 0.01 mag on short-term fluctuations in four classical T Tauri stars. Gullbring et al. (1996) detected flarelike activity in the classical T Tauri star BP Tau, with amplitudes and timescales comparable to that observed in FU Ori; Hessman & Guenther (1997) noted similar behavior in three classical T Tauri stars, DG Tau, DR Tau, and DI Cep. These studies all interpreted the variations with a magnetospheric disk model, where jitter in the magnetically channeled flow from the inner disk to the stellar photosphere produces small amplitude “flares.” We prefer to associate the variation in FU Ori with flickering of the inner accretion disk. The accretion rate in FU Ori, $\sim 10^{-4} M_{\odot} \text{ yr}^{-1}$, is a factor of ~ 1000 larger than accretion rates derived for T Tauri stars, which makes it difficult to truncate the disk with the modest magnetic fields, $\lesssim 1$ – 2 kG, detected in pre-main-sequence stars. Future observations can test the magnetic alternative by placing better limits on any periodic component of the photometric variation and by measuring the magnetic field strength.

However these observational issues are resolved, it is

clear that high-precision photometry can probe the physical conditions of the inner accretion disk of a pre-main-sequence star. The amplitudes and timescales of these variations already provide some challenge to theory. The amplitude of the FU Ori variation implies large fluctuations in the physical structure of the disk on short timescales. Flares and other short-term variations in T Tauri stars suggest smaller, but still significant, changes in disk structure close to the central star. Recent hydrodynamical calculations show that the disk structure can change significantly on longer timescales, but theoretical models do not yet address rapid fluctuations in the disk similar to those observed (Kley & Lin 1999). Future calculations that consider this behavior should lead to a better understanding of mass flow in the inner disk in FU Orionis objects and other types of accreting systems.

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