1. INTRODUCTION

FU Orionis systems are a class of exceptionally luminous young stellar objects found in star-forming regions (Hartmann & Kenyon 1996). Originally identified from their very large increases in optical brightness over timescales of years or less (Herbig 1977), a larger group of heavily extincted probable members of the class have been identified by their characteristic infrared spectra, which strongly differ from those of typical T Tauri stars (Reipurth & Aspin 1997; Aspin & Reipurth 2003; Reipurth et al. 2007). Additional support for the identification of these heavily embedded objects comes from recent high-resolution infrared spectroscopy, which indicates that many of these sources are rapidly rotating and exhibit double-peaked absorption line profiles as observed in FU Ori (Greene et al. 2008).

The accretion disk model for FU Ori objects (Hartmann & Kenyon 1996, and references therein) rests fundamentally on the need to explain the peculiar spectral energy distributions (SEDs) of these objects, which are much broader than that of a single temperature blackbody or star, and which exhibit a continuously varying spectral type as a function of wavelength. The disk model naturally accounts for these properties, as observations at longer wavelengths probe increasingly cooler disk regions with later spectral types; our detailed model for FU Ori matches the SED from optical (\( \sim 0.6 \mu m \)) to infrared (\( \sim 2.2 \mu m \)) wavelengths consistent with the assumption of Keplerian rotation. Here we report a spectrum from the Phoenix instrument on Gemini South which shows that differential (slower) rotation continues to be observed out to \( \sim 5 \mu m \). The observed spectrum is well matched by the prediction of our accretion disk model previously constructed to match the observed spectral energy distribution and the differential rotation at wavelengths \( \lesssim 2.2 \mu m \). This kinematic result allows us to confirm our previous inference of a large outer radius (\( \sim 1 \) AU) for the rapidly accreting region of the FU Ori disk, which presents difficulties for outburst models relying purely on thermal instability. While some optical spectra have been interpreted to pose problems for the disk interpretation of FU Ori, we show that the adjustment of the maximum effective temperature of the disk model, proposed in a previous paper, greatly reduces these difficulties.

Key words: accretion, accretion disks – stars: formation – stars: pre-main sequence

2. OBSERVATIONS

A high-resolution spectrum of FU Ori at 4.9\( \mu m \) was obtained at UT 01:00:29 on 2007 February 4 using the Phoenix spectrometer (Hinkle et al. 1998, 2000, 2003) on the 8 m Gemini South telescope. Observations were taken with a two-pixel slit (0.17") for a resolution of \( \lambda/\delta\lambda \approx 75,000 \) over the wavelength range 4.808–5.050\( \mu m \). We observed FU Ori at two positions along the slit for eight 2 minute exposures. We also observed the B2 III star HR1790 for telluric line correction and took 10 flat-field and dark images.

We reduced the data using IRAF. We averaged the flat-field and dark images and subtracted the average dark image from the average flat-field image. This averaged, dark-subtracted flat-field image was then divided into the target spectra. Images at different positions of the slit were differenced to remove the sky and dark backgrounds. We then extracted the spectra using the IRAF apall routine and later combined and flattened the spectra using splot in IRAF. The spectrum of the hot star HR1790 was used to divide out the telluric lines from the FU Ori spectrum.

IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
sure time of 120 s. The resolutions were \( \sim 40000 \) and \( \sim 20000 \) for the blue and red sides respectively. The MIKE data were observed at optical and near-infrared wavelengths: central star model parameters were those used by Zhu et al. (2007) of the fundamental rotational–vibrational transitions of CO. Most of the lines are due to the P-branch spectrum is clearly present, with relatively broad features and is due to a bad pixel. Outside these regions, an absorption correction can be seen at wavenumbers 2010.4, 2010.9, 2011.9, 2012.3 cm\(^{-1}\) which are the result of overlapping double-peaked lines. These features naturally arise in a disk model but would not be seen in rotating star models (unless large polar spots are invoked; see below). In Figure 2 we display a segment of the MIKE spectrum of FU Ori in the wavelength range 7030–7100 Å for comparison with the synthetic Keplerian disk spectrum. We again find good agreement between model and observation, demonstrating that there has been no change in the estimated optical rotational velocity of the object between the observations in Zhu et al. 2007, which we used to set the disk parameters, and this paper. The HWHD of the optical lines in this wavelength range is \( \sim 65 \pm 5 \) km s\(^{-1}\), consistent with HWHD \( \sim 62 \pm 5 \) km s\(^{-1}\) measured by Petrov & Herbig (2008; PH08).

Thus, compared with HWHD of 2 \( \mu \)m CO first-overtone lines \( \sim 36 \pm 3 \) km s\(^{-1}\) and HWHD of 5 \( \mu \)m CO fundamental lines \( \sim 22 \pm 2 \) km s\(^{-1}\), the differential rotation in FU Ori observed over nearly an order of magnitude in wavelength is consistent with Keplerian rotation. The slow rotation observed at 5 \( \mu \)m (HWHD \( \sim 36 \) km s\(^{-1}\)) implies spectral formation at radii out to \( \sim 0.5 \) AU, in agreement with our SED modeling; this supports our conclusion in Zhu et al. (2007, 2008a) that the extent of the high-accretion rate disk is larger than can be explained by pure thermal instability models for outbursts (Bell & Lin 1994).

4. DISCUSSION

The consistency of the variation of rotational velocities as observed over to \( \lambda \sim 0.7–5 \) \( \mu \)m with Keplerian rotation

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4 http://web.mit.edu/~burles/www/MIKE/.

5 This work employed the line lists from Kurucz CD ROM-15
seemingly provides strong evidence for the accretion disk interpretation of FU Ori. However, PH08 recently argued that while the infrared spectrum is that of an accretion disk, the optical spectrum is produced by a rapidly rotating star with a dark polar spot. The PH08 argument against a pure disk model for a central star rests on three main points: there is no evidence for a variation of absorption line width as a function of excitation potential over the wavelength range $\lambda \sim 0.52$–0.86 $\mu$m; there is no evidence for a variation of rotational velocity with wavelength over that wavelength range; and the observed line profiles are more “boxy” or flat-bottomed than the double-peaked profiles of the disk model.

It is important to recognize that the above-listed effects expected for a disk spectrum require not only differential rotation but a temperature gradient as well. A Keplerian disk exhibiting a constant effective temperature would not show any effect of rotational velocity with either excitation or wavelength; and the double-peaked behavior of line profiles only occurs because the outer, slowly rotating regions do not fill in the profile at line center, as these regions are too cool to emit significantly at the wavelength of observation. While the standard steady disk temperature distribution $T_{\text{eff}}^4 \propto \left[1 - (R_i/R)^{1/2}\right] R^{-3}$ is a power law at large radii, it is relatively flat at distances within about twice the inner radius $R_i$. Therefore, observations at long wavelengths which probe the outer disk where the temperature falls rapidly with radius will exhibit stronger rotational velocity variations and more double-peaked line profiles than observations at short wavelengths probing the inner, more nearly isothermal disk.

In Zhu et al. (2007) we were forced to use a maximum disk temperature $T_{\text{max}} = 6420$ K to match the SED of FU Ori, which is lower than the 7200 K maximum temperature adopted in the model used by PH08 (which was based on the earlier model by Kenyon et al. 1988). Lowering the maximum temperature has the effect of making the flatter part of the accretion disk temperature distribution more dominant at optical wavelengths. As shown in Table 1 and Figure 3, this model predicts essentially no variation of line width with lower level excitation potential and a very slight dependence on wavelength in the optical region. (Note that PH08 predict a much larger effect of line width on excitation potential than Welty et al. (1992) for what should be essentially the same disk model; the reason for the large discrepancy is unclear.) In any case, measurement of rotation is best done through cross-correlation using suitable templates, as many of the lines used by PH08 are blends and introduce very large scatter into the model predictions (see Table 1 and Figure 3).

PH08 also noted that their disk model predicts very strong TiO absorption bands at $\sim 7054$ Å and 7087 Å which are not observed. However, as shown in Figure 2, our lower-temperature disk model does not predict strong TiO absorption bands in this region. In addition there is evidence for 7087 Å bandhead absorption in our MIKE spectra, at the level predicted by our disk model. Once again this difference in the predicted disk model spectra arises simply by reducing the maximum disk temperature, which increases the importance of hot inner disk relative to the outer cool disk at the wavelength of observation.
It has long been known that many optical line profiles in FU Ori are less double-peaked than predicted by simple quiescent disk models (Hartmann & Kenyon 1985). There are, however, alternative possibilities to explain the profiles which do not demand abandonment of the accretion disk hypothesis. If, as currently thought, ionized disks accrete through the action of the magnetorotational instability (MRI; Balbus & Hawley 1998), such disks must be turbulent. The disk models with resolved vertical structure computed by Miller & Stone (2000) predict such disks must be turbulent. The disk models with resolved magnetorotational instability (MRI; Balbus & Hawley 1998), currently thought, ionized disks accrete through the action of the MRI in the central layers of the disk, which would tend to wash out the double profile structure. Hartmann et al. (2004) found that that some mildly supersonic turbulence was needed to explain the $^{12}$CO first-overtone lines of FU Ori. It should be noted that the standard steady disk structure may not be completely applicable in the innermost disk. Standard thin-disk models predict that accretion onto a slowly rotating star should give rise to boundary-layer emission with roughly half the system luminosity; this is not observed in FU Ori (Kenyon et al. 1989). Popham et al. (1996) considered disk models which suppress boundary layer radiation; such models exhibit less doubled line profiles in inner disk regions, largely because the angular velocity of the disk departs from Keplerian near the inner disk boundary.

To explain the optical spectrum of FU Ori with a central star, the star would be required to have essentially the same total system luminosity $L \sim 230 L_{\odot}$, and would need to have a radius roughly twice the inner radius of the disk model, $R \sim 10 R_{\odot}$. Such a star cannot be an isolated product of stellar evolution, as it has an implausibly short Kelvin–Helmholtz contraction time $\sim GM^2 R^{-1} L^{-1} \sim 1200$ yr. The energy to power the star would have to come from disk accretion, which would also potentially explain the outburst (Larson 1983). However, as the ratio of optical-to-infrared rotational velocities is consistent with a Keplerian profile, this implies that any central star would have to be rotating nearly at breakup; this means that the assumption of solid-body rotation in the PH08 model is unlikely to be correct. It is also unclear whether the accretion of a large amount of hot disk material would add enough angular momentum to spin up the outer layers of the star to breakup velocity as it expanded the outer atmosphere.

### Table 1

| $\lambda$ (Å) | Ion     | EP (eV) | HWHD (km s$^{-1}$) | Grade* | $\lambda$ (Å) | Ion     | EP (eV) | HWHD (km s$^{-1}$) | Grade |
|-------------|---------|---------|--------------------|--------|-------------|---------|---------|--------------------|-------|
| 5383.37     | Fe i    | 4.31    | ...                | 0      | 6726.66     | Fe i    | 4.61    | 66.2               | 3     |
| 5717.83     | Fe i    | 4.28    | ...                | 1      | 6767.79     | Ni i    | 1.83    | 65.4               | 3     |
| 5772.15     | Si i    | 5.08    | ...                | 0      | 6810.26     | Fe i    | 4.61    | ...                | 1     |
| 5775.08     | Fe i    | 4.22    | ...                | 1      | 6814.94     | Co i    | 1.96    | ...                | 0     |
| 5862.35     | Fe i    | 4.55    | ...                | 0      | 6828.59     | Fe i    | 4.64    | 78                 | 3     |
| 5899.29     | Ti i    | 1.05    | 61.3               | 2      | 7090.38     | Fe i    | 4.23    | 66.8               | 4     |
| 5922.11     | Ti i    | 1.05    | 61.8               | 3      | 7122.19     | Ni i    | 3.54    | 66.1               | 4     |
| 5934.66     | Fe i    | 3.93    | 78.4               | 3      | 7344.70     | Ti i    | 1.46    | 76.8               | 2     |
| 5965.83     | Ti i    | 1.88    | 65.9               | 3      | 7393.60     | Ni i    | 3.61    | 68                 | 3     |
| 5987.07     | Fe i    | 4.80    | 71.7               | 3      | 7445.75     | Fe i    | 4.26    | ...                | 0     |
| 6016.66     | Fe i    | 3.55    | ...                | 1      | 7511.02     | Fe i    | 4.18    | 61.7               | 4     |
| 6024.06     | Fe i    | 4.55    | ...                | 1      | 7525.11     | Ni i    | 3.63    | ...                | 1     |
| 6027.05     | Fe i    | 4.09    | ...                | 0      | 7555.60     | Ni i    | 3.85    | 68.3               | 3     |
| 6056.01     | Fe i    | 4.73    | ...                | 1      | 7568.89     | Fe i    | 4.28    | 69.4               | 4     |
| 6108.11     | Ni i    | 1.68    | ...                | 1      | 7574.04     | Ni i    | 3.83    | ...                | 1     |
| 6180.20     | Fe i    | 2.73    | 70                 | 2      | 7586.01     | Fe i    | 4.31    | 65.8               | 5     |
| 6270.23     | Fe i    | 2.86    | 72.2               | 3      | 7727.61     | Ni i    | 3.68    | 65.4               | 4     |
| 6355.03     | Fe i    | 2.85    | 64.4               | 3      | 7780.55     | Fe i    | 4.47    | 65.4               | 4     |
| 6358.70     | Fe i    | 0.86    | 66.05              | 4      | 7788.94     | Ni i    | 1.95    | 64.1               | 4     |
| 6380.74     | Fe i    | 4.19    | 72.2               | 3      | 7855.44     | Fe i    | 5.06    | 62.1               | 4     |
| 6411.65     | Fe i    | 3.65    | 67.8               | 2      | 7912.87     | Fe i    | 0.86    | ...                | 0     |
| 6439.08     | Ca i    | 2.53    | 74.5               | 3      | 7937.13     | Fe i    | 4.33    | 63.5               | 4     |
| 6471.66     | Ca i    | 2.53    | 72.8               | 3      | 8075.15     | Fe i    | 0.92    | ...                | 0     |
| 6475.62     | Fe i    | 2.56    | 66.3               | 5      | 8080.55     | Fe i    | 3.30    | ...                | 0     |
| 6569.22     | Fe i    | 4.73    | 67.8               | 5      | 8085.18     | Fe i    | 4.45    | 64.7               | 3     |
| 6581.21     | Fe i    | 1.49    | 64.7               | 4      | 8426.51     | Ti i    | 0.83    | ...                | 0     |
| 6586.31     | Ni i    | 1.95    | ...                | 1      | 8611.80     | Fe i    | 2.85    | 65.0               | 4     |
| 6707.89     | Li i    | 0.00    | ...                | 0      | 8621.60     | Fe i    | 2.95    | 63.5               | 3     |
| 6717.68     | Ca i    | 2.71    | 69.0               | 4      | 8648.47     | Si i    | 6.21    | 73.9               | 3     |
| 6721.85     | Si i    | 5.86    | 65.2               | 2      | 8689.47     | Fe i    | 4.26    | ...                | 0     |

Notes: HWHD means "half-width at half-depth" as illustrated and defined in Figure 3 of PH08. Grade indicates the amount of line blending due to rapid rotation: grades 0 and 1 signify badly blended lines, grade 2 identifies less-blended lines that are difficult to use, and grade 3 means that the line is moderately blended so that the true HWHD may be slightly smaller than our measured value to within 10 km s$^{-1}$. Grade 4 means the line is slightly blended with an errorbar of only 3 km s$^{-1}$, while grade 5 means that the line is blend-free.
In summary, the accretion disk model for FU Ori provides a coherent explanation of the observed spectral energy distribution and differential rotation over more than a decade in wavelength. The slow rotation observed at 5 μm supports our previous result that the high mass accretion rate disk could extend to 0.5–1 AU, which is significantly larger than that predicted by the pure thermal instability theory (Bell & Lin 1994). On the other hand, the theory incorporating both gravitational and magnetorotational (Gammie 1999; Armitage et al. 2001; Book & Hartmann 2005; Zhu et al. 2008b) successfully predicts an AU scale high mass accretion rate inner disk during outbursts (Zhu et al. 2008b). With the advent of more powerful computers and sophisticated magnetohydrodynamic codes, and the assumption of MRI-driven accretion, it should be possible to explore the possibility that atmospheric turbulence and/or nonstandard inner thin disk structure can explain details of the optical line profiles.

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