The Astrophysical Journal, 507:L149–L152, 1998 November 10

FU ORIONIS RESOLVED BY INFRARED LONG-BASELINE INTERFEROMETRY AT A 2 AU SCALE

F. Malbet,[1] J.-P. Berger,[1] M. M. Colavita,[2] C. D. Koresko,[3] C. Beichman,[2,4] A. F. Boden,[2] S. R. Kulkarni,[3] B. F. Lane,[3] D. W. Mobley,[2] X. P. Pan,[3] M. Shao,[2] G. T. Van Belle,[2] and J. K. Wallace[2]

Received 1998 April 22; accepted 1998 August 26; published 1998 September 24

ABSTRACT

We present the first infrared interferometric observations of a young stellar object with a spatial projected resolution better than 2 AU. The observations were obtained with the Palomar Testbed Interferometer (PTI). FU Orionis exhibits a visibility of $V^2 = 0.72 \pm 0.07$ for a 103 ± 5 m–projected baseline at $\lambda = 2.2$ μm. On the spatial scale probed by the PTI, the data are consistent with both a binary system scenario (a maximum magnitude difference of 2.7 ± 0.5 mag and the smallest separation of 0.35 ± 0.05 AU) and a standard luminous accretion disk model ($\dot{M} \sim 6 \times 10^{-5}$ $M_\odot$ yr^{-1}), where the thermal emission dominates the stellar scattering, and are inconsistent with a single stellar photosphere.

Subject headings: accretion, accretion disks — circumstellar matter — infrared: stars — instrumentation: interferometers — stars: individual (FU Orionis) — stars: pre–main-sequence

1. INTRODUCTION

FU Orionis is the prototype of a class of young stellar objects (YSOs), which are called FU Orionis stars, that have undergone photometric outbursts on the order of 4–6 mag in less than 1 yr (Herbig 1966). A FU Orionis star's luminosity typically peaks at $\sim$500 $L_\odot$ and then appears to decay on a 100 yr timescale. FU Orionis stars exhibit large infrared excesses, double-peaked line profiles, apparent spectral types that vary with wavelength, broad, blueshifted Balmer line absorption, and are often associated with strong mass outflows (see Hartmann & Kenyon 1996 for a recent review on this phenomenon).

The FU Orionis stars have been convincingly modeled as low-mass pre–main-sequence stars (T Tauri stars) that are surrounded by luminous accretion disks. The inferred peak accretion rates are on the order of 10^{-4} $M_\odot$ yr^{-1}. The energy released by the accretion process is radiated at the disk surface, overwhelming the stellar emission. Kenyon & Hartmann (1991) show that an opaque, dusty $A_v \sim 50$ mag, infalling envelope with a cavity along our line of sight is consistent with both the mid-IR excess of FU Orionis stars and the relatively low $A_v \sim 1$–4 mag estimated extinction of the inner source.

The radiative balance between disk emission and gravitational energy released by the accretion process implies that the disk's temperature falls with the $-3/4$ power of radius, leading to anticipated angular sizes on the order of 1 mas in the near-IR at a distance of 450 pc. Malbet & Bertout (1995, hereafter MB95) therefore proposed using infrared long-baseline interferometry to probe the physics of these disks.

In this Letter, we present the first infrared interferometric observations of a YSO, taken with a 4 mas resolution at 2.2 μm using the Palomar Testbed Interferometer (PTI). The corresponding linear resolution is better than 2 AU at the 450 pc distance to FU Orionis. The object is found to be clearly resolved, with a fringe visibility significantly below unity and consistent with, although not unique to, the predictions of the disk model. In § 2, we present the observations, and in § 3, we present the data processing. In § 4, we discuss the results in the context of a number of models.

2. OBSERVATIONS

FU Orionis was observed from 1997 November 1 to 7 (nights 305, 306, 307, 309, 310, and 311) using the PTI. The PTI, located adjacent to the 200 inch (5 m) Hale telescope on Palomar Mountain, California, is a two-element interferometer with a 110 m baseline oriented roughly north-south. The observations were taken in the "single-star" mode, in which the measurement consists of the squared fringe visibility V^2 along the single baseline (Colavita et al. 1994). The fringe was tracked and measured in the K band for 11 scans of 125–130 s each. The Earth rotation provided a limited range of projected baselines: 98 m $\leq B \leq$ 108 m and $55^\circ \leq \theta \leq 73^\circ$. We used HD 42807, located at 9°.4 from FU Ori, as the local calibrator star.[5] Scans of FU Ori were alternated with measurements of HD 42807 to ensure an accurate determination of the system visibility. We also used the other calibrator stars from the night to estimate the system visibility (see § 3).

The apparent magnitudes for FU Orionis are $V = 8.9$, $R = 7.7$, and $K = 4.6$ mag. The object is close to the flux limit of both the acquisition and angle-tracking system and the fringe tracker, so special care was taken during the observations and data reduction to optimize sensitivity and avoid biasing the results. The instrument observing parameters were optimized for FU Ori, and identical settings were used for HD 42807. At the level of accuracy of this experiment, the global calibration is consistent with that obtained with the local calibrators.

3. DATA PROCESSING

Because the faintness of FU Orionis made it necessary to operate in previously little-explored regimes close to the sensitivity limits of the instrument, we present here in some detail the data reduction procedures and reliability tests. The data

[1] Laboratoire d'Astrophysique, Observatoire de Grenoble, UMR UJF/CNRS 5571, B.P. 53, F-38041 Grenoble Cedex 9, France; malbet@obs.ujf-grenoble.fr.

[2] Jet Propulsion Laboratory, California Institute for Technology, MS 306-388, 4800 Oak Grove Drive, Pasadena, CA 91109.

[3] Palomar Observatory, California Institute for Technology, 105-24, Pasadena, CA 91125.

[4] Infrared Processing and Analysis Center, California Institute for Technology, M/S 100-22, 770 South Wilson Avenue, Pasadena, CA 91125.

[5] The characteristics from *Hipparcos* catalogue (Perryman et al. 1997) were as follows: $V = 6.5$, G8 V, 55 mas parallax. The estimated K magnitude was 4.7 mag; the estimated diameter was 0.45 ± 0.03 mas.

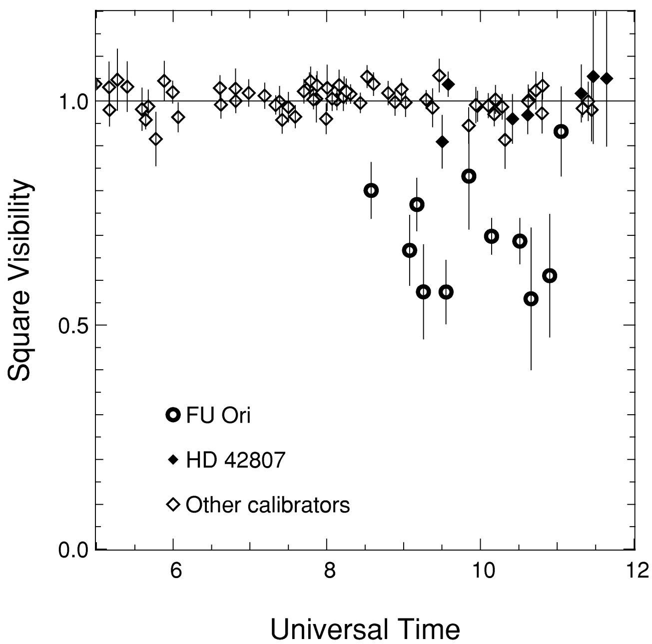

FIG. 1.—Calibrated square visibilities of FU Ori (*open circles*) and its calibrators (*diamonds*) from several nights. The local calibrator HD 42807 is displayed in the filled diamonds.

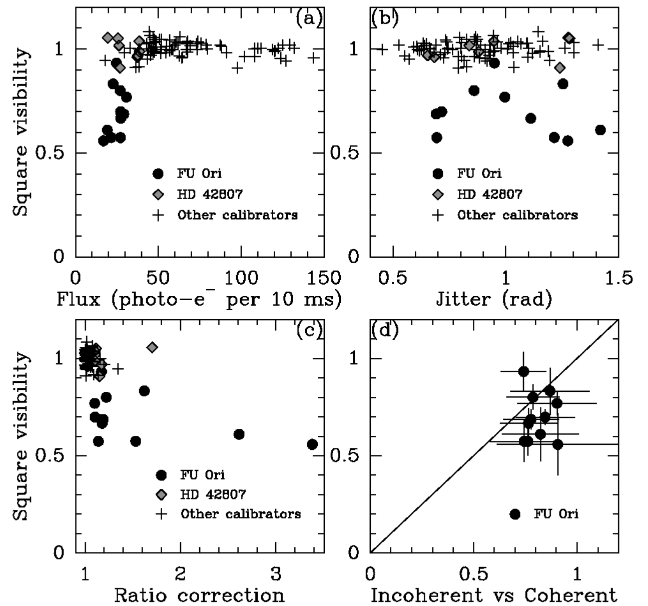

FIG. 2.—Data quality measures: square visibilities vs. (*a*) flux in units of photoelectrons per 10 ms readout vs. (*b*) jitter vs. (*c*) ratio correction. (*d*) Incoherent (*y*-axis) vs. coherent (*x*-axis) square visibilities; the crosses represent the error bars.

processing essentially followed the steps detailed in Colavita (1998). We base our results on the spectrometer data rather than on the white-light data, since the high visibilities produced by its single-mode fiber and narrow bandpass outweighed the larger photon rate in the broadband "white-light" channel. To avoid introducing biases and to maximize sensitivity, we employed an incoherent estimator averaged over the entire *K* band. Examination of the other data products was used to help confirm the robustness of the final visibility measurement.

3.1. *Calibrated Visibilities*

We obtained the *raw* square visibilities $V^2_{\rm raw} \sim 0.6 \pm 0.05$ for FU Ori. The critical next step in the processing consists of dividing the raw visibilities by an estimation of the instrument + atmosphere visibility (i.e., the system visibility) to obtain *calibrated* visibilities V^2.

The single-mode fiber eliminates most atmospheric effects except for the *fringe jitter*, which is due to the differential atmospheric piston. The fringe jitter can introduce a bias into the measured visibility that must be estimated and corrected. The first-difference variance phase $\sigma_{\Delta\phi}$ gives an estimate of the jitter that can be used to derive a small multiplicative correction (Colavita 1998). The jitter correction for these FU Orionis data ranges from 0.94 ± 0.05 to 0.98 ± 0.03.

The calibrator stars are used to estimate the system visibility. The *Hipparcos* catalogue (Perryman et al. 1997) provides the spectral type and parallax for each calibrator, from which we estimated their angular diameters. The calibrators are assumed to have uniform surface brightness. The results are not sensitive to this assumption since the calibrator stars are chosen to have diameters much smaller than the interferometer resolution. The system visibilities are fairly constant for each night (see § 3.2), showing that the instrument is rather stable, with $V^2_{\rm inst} \sim 0.87 \pm 0.02$.

Figure 1 displays the calibrated square visibilities V^2 for FU Orionis and its calibrators. The error bars are estimated from the contributions of the fluctuations of $V^2_{\rm raw}$ between subsamples of the individual scans, the jitter-correction errors, and the instrumental visibility errors.

3.2. *Data Quality Measures*

Because the magnitude of FU Ori is close to the limiting magnitude of the PTI, we present the following, unusually detailed discussion of the data quality. We have run several checks on the data to validate the results and the associated uncertainties. The corresponding plots are displayed in Figure 2 and discussed as follows:

Visibility versus stellar flux.—One might imagine that for an object at the detection limit, flux-dependent terms might become important in the calibration of the visibilities. Figure 2*a* displays V^2 data for FU Orionis and its calibrators and shows no decrease in visibility as a function of flux.

Readout noise.—The observations of FU Ori are dominated by the detector readout noise. Colavita (1998) assesses the expected uncertainties for the PTI data. In our observations, the flux $N \sim 20$ photoelectrons per 10 ms readout, the read noise $\sigma \sim 16e^-$, and the total number of samples $M = 12{,}500$ (five spectral channels combined incoherently each with 25 s of 10 ms frames) lead to $\sigma_{V^2} = 0.113$ for each 25 s measurement. The observed statistical error of 0.05 for a 125 s long observation is consistent with the errors computed statistically for $V^2_{\rm raw}$.

Phase jitter.—The effect of the phase jitter, which is due to imperfect tracking of the fringe as it moves because of atmospheric turbulence (piston), is to introduce a bias that decreases the estimated visibility. Colavita (1998) shows that the jitter is related to the convolution of the variance, $\sigma^2_{\Delta\phi}$, of the differences between successive phase measurements with the power spectrum of the piston disturbance. If the power spectrum is dominated by frequencies higher than 10 ms, one finds that the visibility bias is $e^{-C_\Gamma \sigma^2_{\Delta\phi}}$ with $C_\Gamma = 0.04$. A plot of the jitter-corrected V^2 versus $\sigma_{\Delta\phi}$ (Fig. 2*b*) shows no systematic

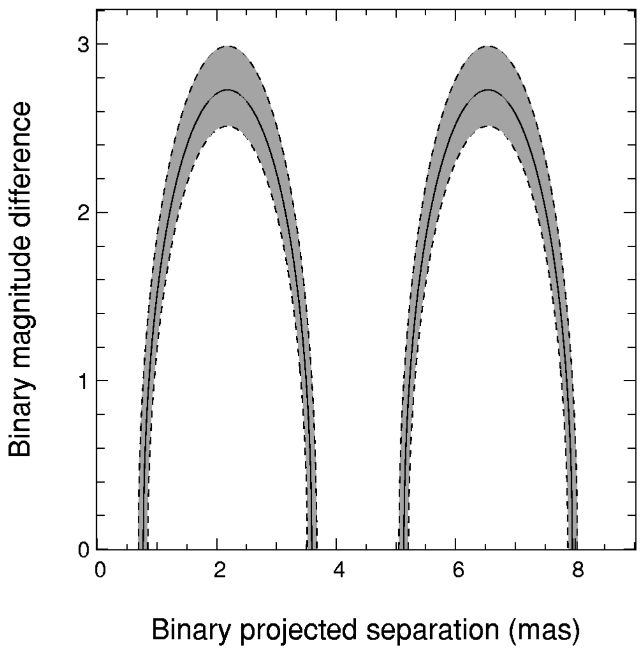

FIG. 3.—Binary scenario: the *K*-magnitude difference vs. the separation projected on the baseline. The shaded region is permitted.

dependence of the visibility on the size of the jitter. We conclude that the data are free of jitter bias. The errors introduced by this jitter correction are on the order of 0.05 for nights 305 and 306, 0.03 for night 307, and 0.04 for nights 309–311.

Flux ratio.—The flux-ratio correction accounts for the difference in fluxes between the two arms of the interferometer, which occurs mainly as a result of optical vignetting. This vignetting results in a bias that decreases the visibility estimation. If this effect is large, measured visibilities should decrease as the correction ratio increases. Figure 2*c* displays the flux-ratio correction versus V^2. Except for the points measured at 10:54 on night 305 and at 10:39 on night 306 that show strong departures, we see no flux-correction effect in the data and have made no correction for it.

Incoherent data versus coherent data.—We processed the coherent data in the same manner as the incoherent data. The effect of jitter is much more important in these data,[6] giving rise to larger uncertainties. The two different measurements are consistent within the uncertainties (Fig. 2*d*), with the coherent visibilities being slightly smaller ($V^2 \sim 0.8$).

White-light data.—The white-light channel is not spatially filtered by a single-mode fiber. This leads to low visibilities, $V^2 \sim 0.3$–0.4, and biases that are difficult to understand. We did not use these measurements to estimate FU Orionis visibilities. However, the FU Orionis raw square visibilities in white-light measurements are always smaller than the calibrator values with a ratio on the order of 0.6–0.7, which is consistent with the spectrometer data.

4. RESULTS AND INTERPRETATION

The calibrated visibilities of FU Orionis display no clear trends with time, projected baseline, or projected angle. We have therefore adopted an averaged visibility value[7] of $V^2 = 0.72 \pm 0.07$ for an averaged projected baseline of 103 ± 5 m and a projected angle of $64° \pm 9°$. Because of the very limited coverage of the visibility space, the current observations cannot provide images of the FU Orionis system that would reveal its morphological structure. The PTI at $\lambda = 2.2\ \mu$m has a spatial resolution of $\lambda/B = 4.4$ mas, corresponding to 2 AU at a distance of 450 pc. *The principal result of this Letter is that FU Orionis is clearly resolved on this angular scale.*

As described in § 1, the double-peaked absorption-line profiles, wavelength-dependent spectral types, and excess infrared emission offer fairly strong evidence for the presence of an active accretion disk. Although there is strong circumstantial evidence for the disk scenario, there has not yet been a direct detection of a physical structure of the predicted extent, and we therefore briefly discuss several alternative interpretations of the new observational result.

Resolved stellar surface.—The angular diameter of a uniformly emitting stellar surface that would give the observed visibility is 1.55 mas, corresponding to a linear diameter of 0.7 AU or 150 $R_\odot$ at the distance of FU Orionis. With a 500 $L_\odot$ luminosity, such a star would exhibit an effective temperature of 2200 K. This interpretation is inconsistent with the observed spectral type by Kenyon, Hartmann, & Hewett (1988, hereafter KHH88), who find spectral types ranging from F7 I for the CN λ3860 lines to K3 for the TiO λ7050 bands. We therefore consider it unlikely that the PTI observations are resolving a bare stellar photosphere.

Resolved binary system.—A second phenomenon that could explain the observed visibility is the presence of a stellar companion. Here we consider a model in which FU Orionis consists of a pair of unresolved stars with angular separation *s* and magnitude difference ΔK. Figure 3 shows the values for the binary parameters permitted by our visibility measurement. The maximum value of ΔK, consistent with the observations, is found to be 2.7 ± 0.5 mag, and the smallest separation *s* is 0.8 ± 0.1 mas, i.e., 0.35 ± 0.05 AU at the distance of FU Ori.

High-resolution spectroscopy (Hartmann & Kenyon 1985, hereafter HK85) reveals double-peaked photospheric lines in the FU Ori spectrum that, at least in principle, could originate from a binary system with an estimated separation $s \leq 0.25(M \sin^2 i/1M)$ AU$_\odot$. Such a model is also compatible with our present data set if the total mass of the system is $\geq 1.4\ M_\odot$, although a considerably more extensive set of observations covering a wide range of projected baseline angles could rule it out. We note that HK85 and KHH88 have favored the accretion disk model to explain the line doubling, because it also succeeds in modeling the spectral energy distribution (SED) and the change of spectral type and line profiles with the wavelength.

Dust halo model.—Many YSOs show large amounts of scattered light in visible and near-IR images (see, e.g., Nakajima & Golimowski 1995 and Burrows et al. 1996). DeWarf & Dyck (1993) fitted their 2.2 μm speckle observations of FU Orionis with a Gaussian halo some 0$''$.07 (35 AU) in diameter, although their data were also consistent with an unresolved object. The PTI data can be fitted by an unresolved star surrounded by a scattering envelope of uniform brightness. The envelope would account for ~15% of the total 2.2 μm flux. Its size is poorly constrained by the PTI visibility measurement: the visibility is insensitive to the size if it is larger than ~10 mas. We argue that depending on the size of the halo, the dust may be seen by direct radiation rather than by scattered light.

The equilibrium temperature of dust close to FU Ori is roughly 270 K$(L/1\ L_\odot)^{1/4}(r/1\ \mathrm{AU})^{\alpha}$ (where α is in the range

[6] $C_\Gamma \sim 0.4 \pm 0.2$, which was measured by fitting $K \exp(-C_\Gamma \sigma^2_{\Delta\phi})$ to the data.

[7] Obtained without the two aberrated points mentioned in § 3.2. With all points, the value is $V^2 = 0.71 \pm 0.08$.

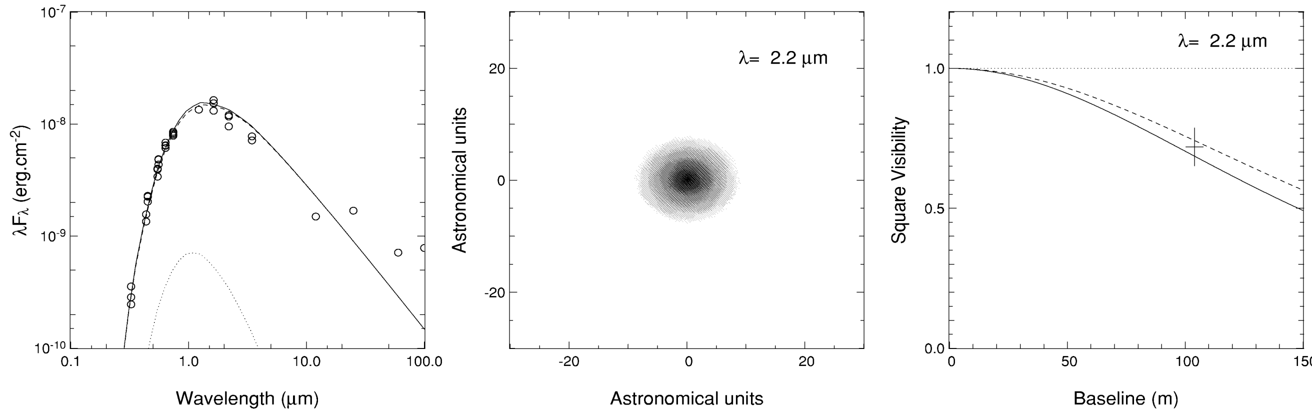

FIG. 4.—Accretion disk model: the left panel displays the SED from the literature data (*circles*) of the accretion disk model (*dashed line*), the star (*dotted line*), and the whole system (*solid line*), the middle panel displays the synthetic image of the accretion disk at 2.2 μm, and the right panel displays the visibility curves of the accretion disk model for the *x*- and *y*-directions (*solid line and dashed line, respectively*). The result of our PTI observation of FU Ori is placed on the figure with its error bars.

$-\frac{1}{2}$ to $-\frac{3}{4}$), depending on the geometrical arrangement of the dust and heating source (Friedjung 1985). The temperature of dust 2 AU from this $L \sim 500\ L_\odot$ object, i.e., at the minimum physical distance resolved by these observations, is ∼750 K; at the 17 AU radius of the halo suggested by the speckle results, it is ∼310 K. Hot material close to the star would emit strongly at 2.2 μm and with an optical depth roughly 5 times greater than the scattering optical depth (Draine & Lee 1984). The ratio of emitted light to scattered light is roughly

$$\frac{B_\nu[T_{\rm gr}(r)]}{\omega B_\nu(T_{\rm eff})(r/R)^{-2}},$$

where ω is the albedo (∼0.2; Draine & Lee 1984), r is the distance to the center, and R and $T_{\rm eff}$ are the equivalent radius and effective temperature of the central source, respectively. With $R = 4\ R_\odot$ and $T_{\rm eff} = 6000$–8000 K, the ratio is much larger than 1 at 2 AU and much smaller than 1 at 17 AU. While a detailed radiative transfer model must be used to assess the relative importance of scattering and thermal emission, we regard thermal emission as likely to be dominant if the radius of the putative dust halo is much smaller than ∼10 AU, whereas scattering will be important if the radius is much larger.

Accretion disk model.—Following MB95, thermal emission from an accretion disk of the type proposed by HK85 and KHH88 is expected to be resolved in the PTI data, with approximately the observed fringe visibility. We computed a disk model with a surface temperature distribution proportional to $r^{-3/4}$ in order to fit the observed SED.[8] The model implies an accretion rate of $\dot{M} \sim 6 \times 10^{-5}\ M_\odot\ {\rm yr}^{-1}$ for a 1 $M_\odot$ star, an $A_V \sim 1$ mag, and an inclination angle of $i \sim 30°$. The resulting synthetic image at 2.2 μm is displayed in Figure 4 (*middle panel*), together with the predicted visibility curves for the major and minor axes (*right panel*). Our interferometric data are in very good agreement with the accretion disk model. However, the precision of the individual visibility measurements is inadequate to constrain the position angle for the disk.

5. CONCLUSIONS

We have resolved a young stellar object for the first time using long-baseline interferometry in the near-infrared, achieving a projected spatial resolution of 2 AU using the Palomar Testbed Interferometer. Although the single visibility measurement presented here can offer only limited constraints on existing astrophysical models, it is reassuringly consistent with the accretion disk that was inferred from earlier spectral and spectrophotometric data. More sensitive multiaperture infrared interferometers like the Keck interferometer and the Very Large Telescope Interferometer, which are now under construction, will soon enable more robust studies by producing true images of the disks of FU Orionis stars with ∼2 AU resolution and even more detailed images of the disks of less luminous T Tauri stars.

[8] The photometry data are from Allen (1973), Glass & Penston (1974), KHH88, and the *IRAS*.

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