THE ASTROPHYSICAL JOURNAL, 490:407–411, 1997 November 20

MULTIPLE DUST SHELLS AND MOTIONS AROUND IK TAURI AS SEEN BY INFRARED INTERFEROMETRY

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Received 1997 April 18; accepted 1997 June 30

ABSTRACT

A visibility curve of IK Tau has been measured with the ISI, an 11 μm stellar interferometer, over a period of several years. Time variations in 11 μm flux were also measured. The results indicate an approximately periodic distribution of dust shells around the star, with shells separated by 200–250 mas and a diameter of about 200 mas for the innermost shell. Some shell motion has been detected, and if velocities are the same as those measured for CO gas and OH masers, the motion implies that the distance to IK Tau is about 265 pc and that shells have been emitted at times separated by about 12 yr, which is considerably longer than the star's luminosity period of 470 days.

Subject headings: infrared: stars — stars: circumstellar matter — stars: imaging — stars: individual (IK Tauri) — stars: mass loss — stars: oscillations

1. INTRODUCTION

Stellar interferometric measurements at 11 μm wavelengths of a number of stars surrounded by dust shells have shown that a considerable fraction of such stars (about half of 15 stars examined) have emitted rather discrete shells. Spacings of the shells indicate that such emissions of material are separated in time by tens to hundreds of years (Danchi et al. 1994; Monnier et al. 1997). However, many other stars surrounded by dust have emitted more continuously, or at least on every luminosity cycle, with typical periods of 1–2 yr. Interferometric observations of IK Tau, otherwise known as NML Tau, during the period 1992–1996 show that it is surrounded by several discrete shells, and in this case shell movement has been detected by interferometric data taken at different epochs. It has been shown that successive dust shells emitted in each luminosity cycle of a star can develop quite differently (Winters et al. 1995). However, in the case of the very large shell separations that have been found, probably including the case of IK Tau, in which the spacing between shells is about 12 yr or 10 luminosity cycles, the discrete shells are probably due to episodic instabilities of the stars rather than dynamic development of dust distributions emitted in each cycle.

2. OBSERVATIONS

Observations were made with the University of California, Berkeley, Infrared Spatial Interferometer (ISI), located at Mount Wilson and operating at 11 μm with various baselines in approximately east-west directions. The interferometer involves two 1.65 m telescopes, each mounted in a movable trailer. Heterodyne detection is used, and lobe rotation maintains interference fringes at a fixed frequency as a star crosses the sky, essentially similar to what is commonly done in radio interferometry. More detailed descriptions of the interferometer are given by Bester et al. (1990).

Observations of IK Tau were carried out during the late summer and early fall, from 1992 to 1996 on a variety of baselines, as indicated in Table 1. Near a wavelength of 1 μm, IK Tau varies by about 2.7 mag, with a period of 470 ± 5 days (Wing & Lockwood 1973). The phases listed in Table 1 represent fractions of a cycle, with maxima designated as 0 or 1. These phases are extrapolated from a systematic determination of a phase and a period of 470 days in 1973 (Wing & Lockwood 1973). *IRAS* measurements have been analyzed by Le Sidaner & Le Bertre (1996) and yield a period of 462 days. Their phase, measured in 1986 and extrapolated into 1992 using this period, would increase the phases used here by 0.08, an unimportant amount for present purposes. Measurements of the 11 μm flux were made with the United Kingdom Infrared Telescope during 1992–1996, utilizing either its single-channel photometer, UKT8, or its linear array spectrometer, CGS3. The measurements are plotted in Figure 1 and are fitted to a sinusoidal variation with peak-to-peak variation of 1.03 mag and a period of 470 days. The phases of 11 and 1 μm fluxes are not necessarily the same for stars with dust shells such as IK Tau, but these 11 μm measurements provide useful assurance that the extrapolated 1973 phases are approximately correct, since phases determined from fitting the data in Figure 1 differ from the extrapolated values by no more than 0.05.

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TABLE 1

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Dates	Baseline Length (m)	Baseline Angle (deg N of E)	Phase of IK Tau
1992 Aug 7, 21, 25, 26 and Sep 3, 8, 9, 10	13.2	23	0.00–0.08
1992 Nov 4	9.6	33	0.20
1993 Sep 3, 14, 15, 25	9.6	33	0.84–0.89
1993 Nov 5	32	28	0.99
1994 Aug 4, 6, 8	32	28	0.56
1994 Sep 15, 20 and Oct 17, 19, 21	4.0	0	0.64–0.72
1995 Oct 18–20, 25 and Nov 7–9	4.0	0	0.50–0.55
1996 Sep 22, 23, 27 and Oct 4, 7, 9, 10	4.0	0	0.20–0.24

3. DISCUSSION OF DATA

The visibility data are shown in Figure 2, with the dates of the various measured values indicated. The visibility curves are clearly more complex than the forms normally found for stars surrounded by a simple dust shell. For this reason, it is important to obtain complete sets of data for IK Tau, so that details of the curves can be determined, rather than only a few data points, which would be sufficient to characterize a simpler intensity pattern. Coverage is complete enough to characterize a number of major features, but some simplifying assumptions must still be made to model the intensity distribution.

The measurements from 1992 and 1993 with 9.6 and 13.2 m baselines and those made in 1996 with a 4 m baseline were at luminosity phases near maximum (see Table 1) and hence should be compatible. The measurements made in 1994 and 1995 with a 4 m baseline are at phases nearer minimum luminosity, which could change their values somewhat in comparison with those of 1996, even with identical dust distributions. However, estimates made from sample dust shell models indicate that at these lower luminosities the visibility values in the range (1.5–3.5) $\times 10^5$ rad^{-1} should be only about 0.03 higher than those for phases nearer maximum luminosity, and that the slope of the visibility curve should be affected very little. Hence, in fitting curves to the data, all points in the range (1.5–5) $\times 10^5$ rad^{-1} are treated as equivalent, regardless of the star's luminosity phase. However, the year when individual points were measured is identifiable by the symbols used, so that any significant difference can be seen.

The fraction of 11 μm radiation produced by the star itself, rather than by warm dust around it, is indicated by the visibility at long baselines. At our highest resolution (25×10^6 rad^{-1}), the star is not resolved, but the dust clearly is. The latter is essentially resolved at about 10×10^5 rad^{-1}, since the visibility is the same there as at 25×10^5 rad^{-1}. These values show that the stellar radiation detected is only about 2%–6% of the total 11 μm flux. However, the optical depth of surrounding dust at 11 μm indicates that the actual stellar flux is several times greater than this amount.

A striking feature of the visibility curve is the rapid drop in visibility in the range of spatial frequencies from about

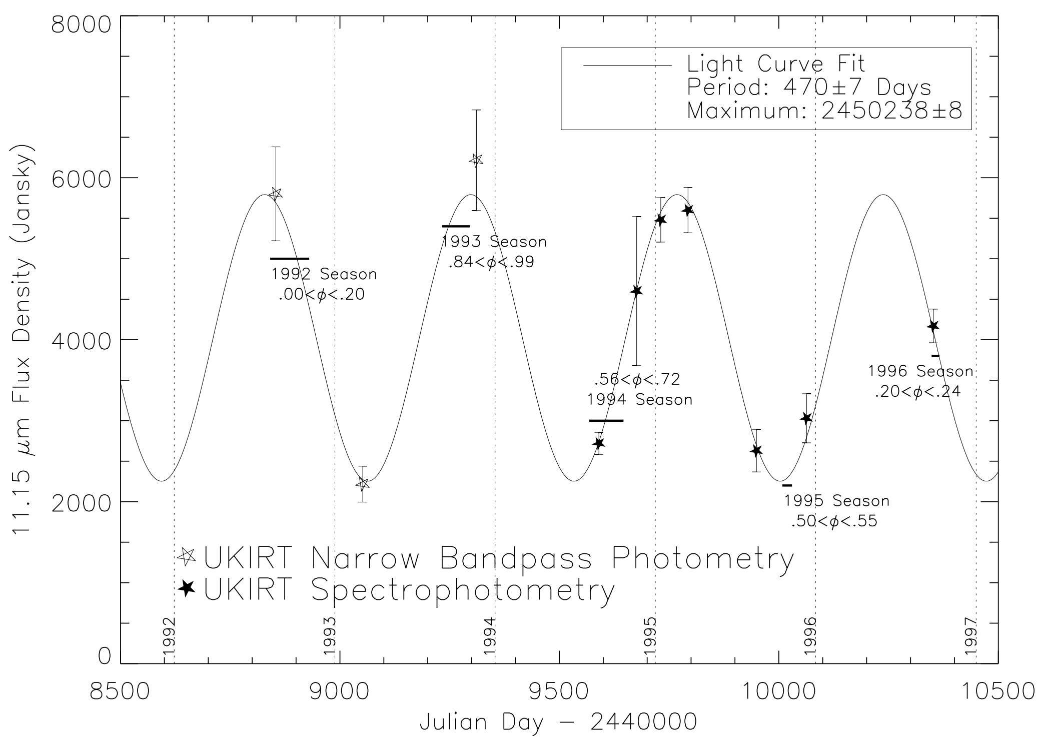

FIG. 1.—Measurements of IK Tau's flux at 11.15 μm as a function of time and best fit to a sinusoidal curve. From this fit, the period is 470 $\pm$ 7 days, peak-to-peak change 1.03 $\pm$ 0.08 mag, and phase zero at Julian Day 2,450,238 $\pm$ 8.

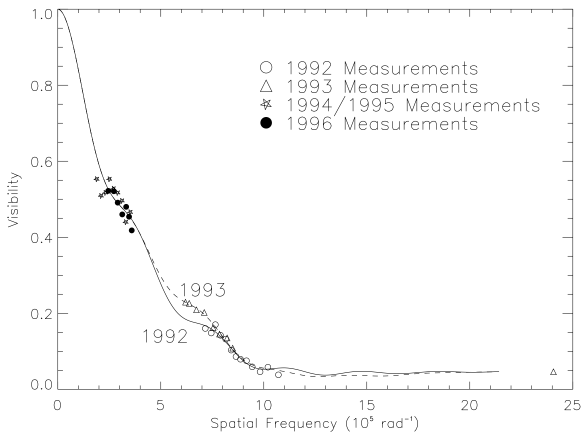

FIG. 2.—Visibility measurements of IK Tau at 11 μm wavelength with the ISI interferometer, 1992–1996. The 1992 and 1993 data differ in the region near 7×10^5 rad^{-1}. Data of 1994 and 1996 agree within reasonable approximation and should also apply to 1992 and 1993. Probable errors are not shown in this case because of the number of points, but consistency between them yields a rough measure of probable errors. The two curves are maximum entropy fits to the 1992 and 1993 data, respectively, each extended by the 1994 and 1996 data. The lowest resolution values, below about 1.5×10^5 rad^{-1}, assume a Gaussian outer distribution of dust.

7×10^5 to about 10×10^5 rad^{-1}, beyond which the slope is much less steep. Furthermore, in the region near 7×10^5 rad^{-1}, the 1992 and 1993 data differ significantly. Data for 1992 in this range of visibility were published previously (Danchi et al. 1994). They also indicated the same distinctive change in slope, but because the visibility measurements covered only a limited range of spatial frequencies, an overly simple model of the dust shell was assumed in fitting the data.

Since the significance of an apparent change in visibility between 1992 and 1993 is of interest, a detailed plot of visibility measurements in the range (6×10^5)–(1.1×10^6) rad^{-1} is shown in Figure 3, with probable errors indicated. Each of these points is the average of three to 10 measurements made on different nights. It may be noted that, although the average infrared luminosities during the measurement periods of 1992 and 1993 were nearly the same, there was as much as a 20% change in luminosity during the measurements. However, this seems not to have affected the visibility averaged over the observing periods significantly, since no systematic changes were noted during each set of measurements, and, in any case, variations that were linear in time would be largely eliminated by the averaging. The visibility values near 7×10^5 rad^{-1} for 1992 and 1993 indicate a clear difference between the two years. In the range $(7–8.5) \times 10^5$ rad^{-1}, the values and probable errors of the 1992 points are weighted means. This provides the most realistic evaluation of probable errors. For all other points, the various measurements have been averaged with equal weighting, and probable errors determined from their consistency. Except for some possible scale factor error, the latter method actually provides upper limits to the error; however, these upper limits are sufficiently small that any further refinement is unimportant to the present discussion. Simple averaging with equal weights for 1992 points in the range $(7–8.5) \times 10^5$ rad^{-1} yields essentially the same general shape of curve as the more precise weighted averages, but with somewhat larger probable errors, which, as noted, would be upper limits.

4. ANALYSIS OF THE MEASURED VISIBILITIES

Measured visibility points have been fitted by curves shown in Figure 2. These curves are derived from intensity distribution models shown in Figure 4, obtained by fitting the observed points to a model intensity profile that is circularly symmetric, using the maximum entropy method. Measurements in the range $(1.5–3.5) \times 10^5$ rad^{-1} during different years and phases agree reasonably well, as discussed above, and have been used for both the years 1992 and 1993. No 1993 data are available in the region $(8.5–12) \times 10^5$ rad^{-1}, so the data of 1992 are assumed to approximately apply for 1993. However, in the range $(6–8.5) \times 10^5$ rad^{-1}, the data of 1992 and 1993 appear to differ. Hence, the two different maximum entropy curves shown in Figure 2 are constructed to fit the somewhat different visibility values obtained for 1992 and 1993 in this range. In the very low resolution range, less than 1.5×10^5 rad^{-1} ($> 1''.3$), a somewhat arbitrary Gaussian intensity distribution was assumed in order to extrapolate for a visibility of unity. This low-resolution part of the visibility curve is not very important to the general conclusions of this analysis. Because there are gaps in the visibility

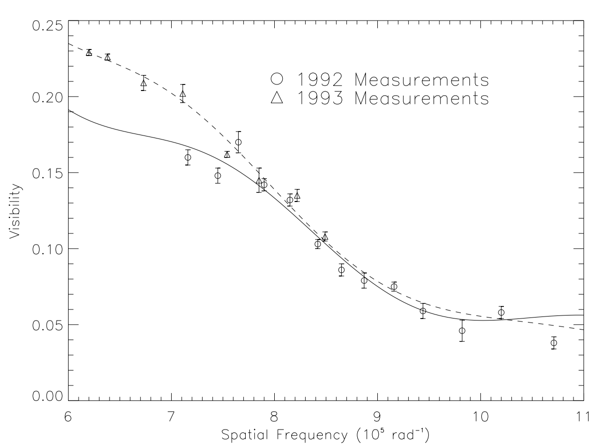

FIG. 3.—Part of visibility data and maximum entropy curves for IK Tau at 11 μm wavelength in 1992 and 1993. The probable error of each point is shown so that change between the two years can be evaluated.

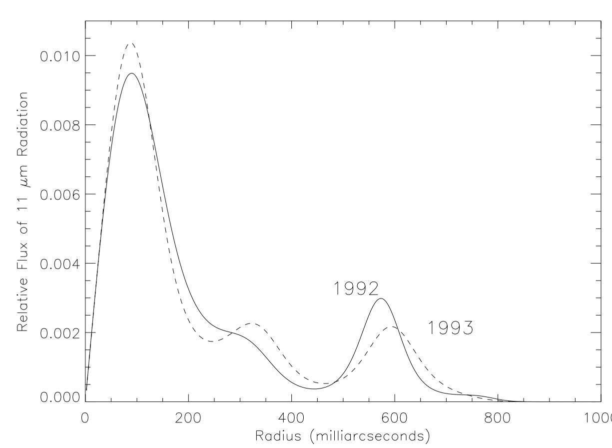

FIG. 4.—Radial intensity distribution of 11 μm radiation derived from the two maximum entropy curve fits of Fig. 2. Ordinates are proportional to the total intensity in a narrow ring about the star of radius given by the abscissae. The solid curve fits the 1992 data, and the dashed one the 1993 data. A more or less periodic shell structure and some motion from 1992 to 1993 is seen.

measurements, the maximum entropy curves plotted are not unique solutions. However, in Figure 2 they indicate reasonable interpolations between measured points.

If spherical symmetry of the star and dust shells is assumed, the two visibility curves of Figure 2 are each uniquely produced by the radial distributions of 11 μm radiation shown in Figure 4. Evidence that the dust distribution is, at least, approximately spherical has been obtained by images taken from aperture-masking interferometry on the 10 m Keck Telescope at 2.2 and 3.1 μm wavelengths (P. Tuthill, W. C. Danchi, C. Haniff, E. Lipman, J. D. Monnier, & E. Wishnow 1997, private communication). The 3.1 μm radiation produced an approximately circular image detected out to a diameter of about 140 mas with a resolution of 40 mas. Ordinates of the curves in Figure 4 are proportional to the total 11 μm intensity in a thin circle about the star of a radius given in arcseconds by the abscissae. For both distributions, there is a dust shell of radius about 100 mas, or diameter of 200 mas, and two more or less discrete shells separated by about 240 mas. This approximately regular spacing is what produces a hump in the visibility curve in the (6–8.5) $\times 10^5$ rad^{-1} range, though in somewhat different positions for the two years. It can be seen from Figure 4 that the prominent and well-defined outer dust shell expanded between 1992 and 1993. One should not expect that each dust shell emitted has exactly the same velocity, but if the motion of the outer shell is taken as 20.5 km s^{-1}, an average of the 22 km s^{-1} velocity measured by CO line emission of material surrounding the star (Knapp & Morris 1985) and of 18.7 km s^{-1} for OH masers (Bowers et al. 1989), then the stellar distance can be obtained from the observed motion. The displacement of the outer shell is 17 mas between average dates of 1992 August 24 and 1993 September 14. From these values, the stellar distance is calculated to be 265 pc. This is in good agreement with the estimates of 270 and 220 pc by Knapp & Morris (1985) and Le Sidaner & Le Bertre (1996), respectively. Other estimates in the literature for the distance to IK Tau vary from 240 to 500 pc (Knapp & Morris 1985). If the velocity of the outer shell is indeed close to the average of OH and CO gas measured by microwave astronomy, the distance of 265 pc should be approximately correct and should confirm the distance estimates that have arrived at comparable values, rather than others that are substantially different.

If the true velocity of each shell is 20.5 km s^{-1}, then the angular separation between the shells and the distance of 265 pc allow a determination of the time between their emissions, which is about 12 yr.

A brief qualitative discussion of the visibility curve and its interpretation, in addition to the mathematical curve fitting carried out for Figure 4, is perhaps of some value for an understanding of which parts of the models shown in Figure 4 are most significant. A single shell of dust would have a visibility curve that decreases smoothly to zero as the resolution is increased and, after the first zero, would produce some small bumps. Continuously emitted dust, with density distribution proportional to $1/r^2$ as a function of distance r from the star, would also decrease smoothly to zero, rather than producing the hump found in the case of IK Tau. The hump thus indicates a structure for the dust distribution that is characterized by some periodicity, and its sharpness indicates that a particular spacing is probably repeated several times to produce a rather well defined spatial frequency in the visibility curve. Thus the feature at 8×10^5 rad^{-1} can be expected to indicate at least two or more maxima in intensity at this spatial frequency, i.e., peaks separated by about 250 mas, as seen in Figure 4.

For 1993, the visibility curve of Figure 2 is noticeably different from that of 1992 in the region near 8×10^5 rad^{-1}. In 1993, the fairly steep rise continues toward smaller inverse radians than in 1992 and flattens out somewhat near 7×10^5 rad^{-1} instead of 8×10^5 rad^{-1}. Where this change in slope takes place is not as clear in 1993 as it is in 1992. Fading out of this unusual hump in visibility is expected as the shells move, even if they all move at the same rate, since constant expansion would not allow their separation to continue to equal the diameter of the innermost shell. The apparent change in position of the hump in the visibility curve, from about 8×10^5 rad^{-1} in 1992 to about 7×10^5 rad^{-1} in 1993, immediately allows for a rough estimate of the distance to the star, if the velocity is known. This distance D is given by

$$\frac{1}{7 \times 10^5} - \frac{1}{8 \times 10^5} = \frac{2vt}{D}, \quad (1)$$

where v is the radial velocity and t is the elapsed time of approximately 1.05 yr. With a measurement of $v = 20.5$ km s^{-1} for surrounding gas, D equals 240 pc. This estimate, using visual observations of the visibility curves, is close to the 265 pc obtained above with a more detailed curve-fitting calculation.

The middle intensity peak of Figure 4 is overlain by the inner shell enough that its motion cannot be very well determined. But the innermost shell, with a radius of about 100 mas, has approximately the same position in 1992 and 1993, according to Figure 4. This could be because its velocity is small. However, its position is determined to a considerable extent by the part of the curve in Figure 2 that decreases rapidly in the region from 8×10^5 to 12×10^5 rad^{-1}. For the higher resolution part of this region, no data are available from 1993, so 1992 data were used as an approximation for the 1993 visibility curve. The constancy of position of this peak hence could be an artifact due to lack of more complete 1993 data. However, a number of past measurements of water vapor masers indicate that material has been present at this same radius for at least a decade.

Interferometric measurements of 22 GHz H_2O maser positions and velocities around IK Tau have been made over a period of 11 years. Lane et al. (1987) found, from measurements in 1983, an approximately spherical distribution of H_2O masers with radius close to 100 mas and expansion velocity 15.5 km s^{-1}. Bowers et al. (1993) find in 1985 a shell of radius about 110 mas and an expansion velocity of about 17 km s^{-1}. Rosa-Gonzalez (1996) finds, in 1994, a comparable velocity range and a distribution of H_2O maser intensity, with maxima at a radius of about 100 mas. These observations place the masers close to the inner shell of Figure 4. If the shell has been expanding at the measured H_2O maser velocities and a distance of 270 pc is assumed, its radius should have expanded by as much as 130 mas over the 11 year interval 1983–1994. Dynamics of the shell are not clear, but the H_2O measurements are consistent with the present infrared interferometry, showing no substantial motion of the innermost shell over the 1 year between measurements.

Figure 4 displays the 11 μm intensity as a function of distance from the star, not the density of dust. A detailed radiative transfer calculation is needed to obtain details of the dust density and temperature distributions. However, a rough approximation for the amount of dust is given by the simplified solution in Danchi et al. (1994), where the average dust outflow was found to be about $5 \times 10^{-6}\ M_{\odot}\ \mathrm{yr}^{-1}$, agreeing reasonably with values obtained from radio-frequency molecular measurements.

5. CONCLUSIONS

Multiepoch visibility measurements have been made on IK Tau with high-resolution interferometry in the mid-IR. From these results, it is shown that there is an approximately periodic shell structure of dust surrounding the star, with shells of radii about 100, 320, and 570 mas. Some motion of the outer shells is detected; the outermost shell appears to have moved about 17 mas between 1992 August and 1993 September. Use of measured gas velocities allows the conclusions that the time between emission of shells of material is about 12 yr, and that the stellar distance is approximately 265 pc.

The authors thank R. J. Cohen for providing information from the thesis of D. Rosa-Gonzalez. This work was supported by grants from the Office of Naval Research (grant N00014-96-0737) and from the National Science Foundation (grants AST 90-16474, AST 93-15485, and AST 93-21289). M. J. was supported under the auspices of the US Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

REFERENCES

Bester, M., Danchi, W. C., & Townes, C. H. 1990, Proc. SPIE, 1237, 40
Bowers, P. F., Claussen, M. J., & Johnston, K. J. 1993, AJ, 105, 284
Bowers, P. F., Johnston, K. J., & de Vegt, C. 1989, ApJ, 340, 479
Danchi, W. C., Bester, M., Degiacomi, C. G., Greenhill, L. J., & Townes, C. H. 1994, ApJ, 107, 1469
Knapp, G. R., & Morris, M. 1985, ApJ, 292, 640
Lane, A. P., Johnston, K. J., Bowers, P. F., Spencer, J. H., & Diamond, P. J. 1987, ApJ, 323, 756
Le Sidaner, P., & Le Bertre, T. 1996, A&A, 314, 896
Monnier, J. D., et al. 1997, ApJ, 481, 420
Rosa-Gonzalez, D. 1996, Master's thesis, Univ. Manchester
Wing, R. F., & Lockwood, G. N. 1973, ApJ, 184, 873
Winters, J. M., Fleischer, A. J., Gauger, A., & Sedlmayer, E. 1995, A&A, 302, 483