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LOCATION AND PHASE OF DUST FORMATION IN IRC +10216 INDICATED BY 11 MICRON SPATIAL INTERFEROMETRY

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ABSTRACT

A new long-baseline interferometer for the 10 μm region has provided visibility measurements of IRC +10216 at spatial frequencies in the range 1.4–12 $\times 10^5$ rad^{-1}. These show large changes in visibility with phase of the LPV's luminosity. Model fitting of the visibility curves indicates that dust forms closer to the star ($\sim$3 and $\sim$2.5 times the stellar radius at maximum and minimum luminosity, respectively) and at higher temperatures ($\sim$1300 K) than has been indicated by previous measurements. In addition, new dust appears to form near minimum luminosity. There is general agreement with previous theoretical expectation that dust should form at temperatures above about 1300 K and that close to the star the material is less transparent at mid-IR wavelengths than in the near-IR.

Subject headings: interferometry — stars: carbon — stars: circumstellar shells — stars: individual (IRC+10216) — stars: mass loss — radiative transfer

I. INTRODUCTION

The long-period variable star IRC +10216 and its surrounding dust shell provide one of the brightest infrared stellar sources as seen from Earth. A wide variety of measurements have been made in the past which show that it is a carbon star (Herbig and Zappala 1970) and give a luminosity varying by a factor of 2 with a period of approximately 640 days. In 1983 the maximum luminosity was 5.6×10^4 $L_\odot$ if the distance assumed is 300 pc and had been slowly decreasing with time (Le Bertre 1988; Ridgway and Keady 1988; Witteborn *et al.* 1980). The star is surrounded by a dust shell with a total width at half-maximum of approximately 0".9 for 10 μm radiation, a mass-loss rate of about 2.5×10^{-5} $M_\odot$ yr^{-1} (Le Bertre 1988; Martin and Rogers 1987; Bloemhof *et al.* 1988; Benson, Turner, and Dyck 1989), and a terminal outflow velocity near 15 km s^{-1} (Goldhaber 1988; Knapp and Morris 1985; Zuckerman, Dyck, and Claussen 1986). Both speckle and Michelson interferometry have been carried out at a wide variety of wavelengths to determine the shape and density of the dust shell, and the inner radius where dust formation begins. These have indicated an approximately spherical shape for the dust radiation near 10 μm wavelength (Le Bertre 1988; Dyck *et al.* 1987; Sutton *et al.* 1979; Sutton 1979), though there are distinct variations from sphericity at shorter IR wavelengths, some of which may be associated with scattering. They also have indicated that dust forms at angular radii somewhere between about 0".09 and 0".2 at a temperature of about 1100 K (Le Bertre 1987, 1988; Ridgway and Keady 1988; Rowan-Robinson *et al.* 1986; Sutton *et al.* 1979).

A newly constructed interferometer, presently operating at a central wavelength of 11.15 μm, has allowed us to measure visibilities of IRC +10216 in some detail at various phases, and with longer baselines than have previously been reported for this object. The measurements show, somewhat unexpectedly, that the dust appears to form closer to the star and at appreciably higher temperature than previously thought, and that the visibility changes substantially with phase. Furthermore, dust formation is particularly marked close to the minimum luminosity phase.

II. INSTRUMENTATION

The Infrared Spatial Interferometer (ISI) has been described in several papers (Danchi, Bester, and Townes 1988; Bester *et al.* 1989; Bester, Danchi, and Townes 1990), and hence it is discussed only briefly here. The ISI operates in the 9–11 μm atmospheric window and is located at Mount Wilson (1742 m). It comprises two compact telescopes of 1.65 m aperture. To ensure mobility, all optics and electronics for each telescope are mounted within a standard-size semitrailer. Heterodyne detection is used, with liquid N_2 cooled HgCdTe photodiodes and phase-locked CO_2 laser local oscillators (LO). Correlation of the received signals over the IF passband is maintained with an IF coaxial delay line. A lobe rotator acting on the LO system is used to move the fringes from their natural frequency to a fixed frequency of 10 Hz. Sample fringe spectra from IRC +10216 are shown in Figure 1. They represent typical results for average (Fig. 1*a*) and excellent (Fig. 1*b*) seeing conditions. With good seeing, the widths of the central spikes are determined only by the integration time, which in these cases is 44 minutes so that the widths are 0.38 mHz.

Visibilities are obtained from the ratio of power in the 10 Hz fringe signal (itself a product of amplitudes in the two telescopes) to the product of the total signal power from the star received in each telescope. This ratio is proportional to the square of the visibility even under poor seeing conditions since, with heterodyne detection, the signal power received by each telescope is only that component of the wave which is coherent with the wavefront of the laser LO, and signals received in each telescope from a point source will then be fully coherent with each other. However, some frequency modulation of the fringe is produced by relative variations in path lengths through the atmosphere to the two telescopes. For this reason, the power in the fringe signal is taken as the total fringe power in a 2.5 Hz bandwidth about the central 10 Hz frequency. Figure 1 shows sidebands around the central fringe frequency produced by path length fluctuations under two different seeing conditions; essentially all the fringe signal power is well within a 2.5 Hz bandwidth.

While the ratio of the fringe signal power to the product of

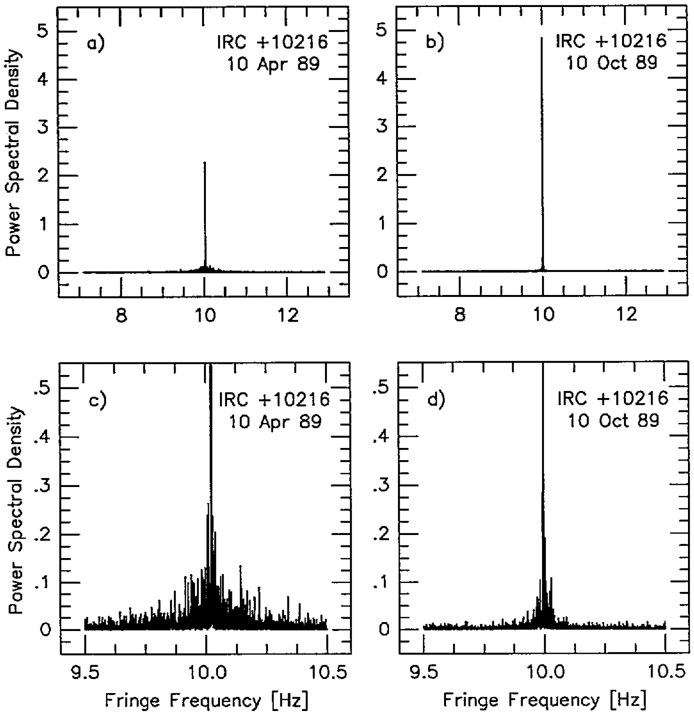

FIG. 1.—Interference fringes of IRC +10216 (*a*) under average seeing conditions and (*b*) with excellent seeing; each spectrum represents 44 minutes of observation. Figs. 1*a* and 1*b* are magnified in both axes in (*c*) and (*d*), respectively, in order to expose the sidebands due to fluctuations in relative path lengths through the atmosphere. In each case the central spike has a frequency width equal to the inverse of the observing time, or 0.38 mHz.

signal power in each telescope is proportional to the square of the visibility, this ratio must be calibrated so that the visibility is unity for a point source. For this purpose, we calibrate by observing α Tau, α Her, and the central star of α Ori; visibility of the latter two have been previously measured by Sutton *et al.* (1979). These three sources give results consistent within 5%, and there has been no substantial change in calibration from 1988 October to 1989 December. Hence a fixed calibration factor has been used for all the visibility data; we believe it correct in absolute value to within 5%.

III. OBSERVATIONS

Visibilities were measured with a 4 m E-W baseline on UT 1988 October 4 and 8, and in UT 1989 on April 8, 9, and 10, June 16, July 5 and 7, and October 10 and 19. Measurements were also made with a 13 m baseline, at an angle of 22° from the E-W direction, on UT 1989 November 9 and 15, and December 5.

Figure 2 represents visibility measurements separated into two groups corresponding approximately to maximum and minimum stellar luminosities. Maximum luminosity ($\phi = 0$) occurred near UT 1988 November 12 (Le Bertre 1988; Ridgway and Keady 1988; Joyce 1990). Minimum ($\phi = 0.5$) would occur on 1989 September 28 if the variation were sinusoidal, but the minimum is systematically delayed 10–20 days later than this. Visibilities at an intermediate phase were also obtained from the June and July measurements. If for simplicity the luminosity is assumed to vary sinusoidally between $4.2 \times 10^4\ L_\odot$ and $2.1 \times 10^4\ L_\odot$ with a period of 640 days, the three groups of data would have ranges of phase and luminosity as follows: 1988 October 4–1989 April 10, $\phi = 0.989$–0.232, $L = 4.20$–$3.27 \times 10^4\ L_\odot$; 1989 June 16–1989 July 7, $\phi = 0.337$–0.370, $L = 2.60$–$2.43 \times 10^4\ L_\odot$; 1989 October 10–1989 October 19, $\phi = 0.519$–0.533, $L = 2.11$–$2.12 \times 10^4\ L_\odot$. While visibility data within any one of these groups are in rather good agreement, it is clear that the visibility changes markedly with phase of the stellar luminosity. Visibilities obtained with a 5.5 m baseline near $\phi = 0$ in 1978 by Sutton *et al.* (1979) with a prototype of the present interferometer are also included in Figure 2.

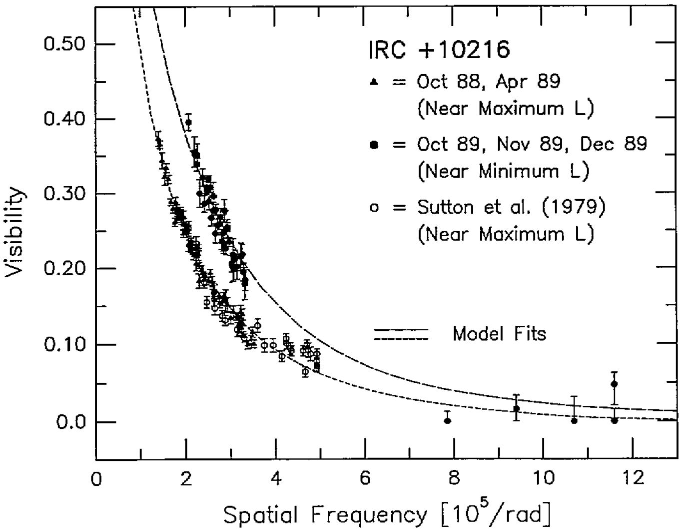

FIG. 2.—IRC +10216 visibilities as a function of spatial frequency near maximum and minimum of the LPV's luminosity cycle, showing large changes with phase. The data represent both the present measurements made in 1988 and 1989 and, in the spatial frequency range 2–5 × 10^5 rad^{-1}, data of Sutton *et al.* (1979) taken near maximum luminosity in 1978 February and April. (Sutton 1979). Model fits use parameters of Table 1.

Visibility measurements at spatial frequencies of 7–12 × 10^5 rad^{-1} (13 m baseline) show immediately that the visibilities of about 0.10 measured by Sutton *et al.* (1977, 1979) in the range 4–5 × 10^5 rad^{-1} and which appeared to be due to the central star were in fact largely due to dust which is resolved at a 13 m baseline. Hence the inner radius of the dust must be substantially less than previously indicated by these measurements and by a number of measurements at shorter wavelengths (cf. Le Bertre 1988). Visibilities were measured as $\lesssim 0.03$ with the longer baseline in the late fall of 1989 during the star's luminosity minimum. Since luminosity increases the dust radiation at 11 μm more than that of the star, the visibility during maximum luminosity must be at least as small. The contribution to the 11 μm visibility from the star may also be estimated from the ratio of bolometric intensity to the 11 μm flux, assuming a stellar temperature. For standard values of these quantities, the maximum visibility at $\phi = 0.5$ is 0.028 if the stellar temperature is 2018 K, consistent with the measured result; dust shell optical depth, τ, decreases this value by the factor $e^{-\tau}$.

IV. MODELS OF THE STELLAR SYSTEM

To calculate visibilities, we have used a model in which the dust is spherical in distribution, uniform in nature, and varies in density as r^{-2}, where r is the distance from the star. In addition, dust temperature is assumed to vary as $r^{-\alpha}$, where α is a variable to be fitted. For a dust opacity varying with wavelength as λ^{-n}, $\alpha = 2/(4 + n)$ if radiation equilibrium at each radius is assumed. Thus Le Bertre (1987) takes $n = 1.3$ and

$\alpha = 0.38$. The flux of IRC +10216 at 11.15 μm, measured by T. Geballe on 1989 November 1 near luminosity minimum, was 25,500 Jy. This flux, as well as the factor of 2 variation in stellar luminosity between maximum and minimum are taken as constraints. A further constraint is that the dust distribution at $\phi = 0$ must remain in place at $\phi = 0.5$, though formation of new dust may change the inner radius R_C a small amount between the two phases. In changing R_C, we assume the dust is everywhere of uniform composition and density is proportional to r^{-2}, so that the total optical depth at 11.15 μm is proportional to R_C^{-1}.

With the above constraints, the variables R_C (the inner radius), τ (the optical depth), and α (the temperature power law) remain. A temperature variation $r^{-\alpha}$ with a constant power law α can only be approximate because the dust opacity is a complex function of the wavelength rather than simply proportional to λ^{-n}. In particular, the large absorption by dust of wavelengths near 10 μm should make the value of n decrease and that of α increase somewhat as the radiation temperature decreases to a point where most of the energy is carried by radiation in the mid-infrared rather than the near-infrared. A still better approximation would be to calculate dust temperature from a detailed knowledge of its radiation characteristics. Martin and Rogers (1987) have made such a calculation for particular dust characteristics, but we find their model fits our measured visibilities poorly, and hence we use the power-law approximation $r^{-\alpha}$ for the temperature variation. In all cases, visibility calculations have included allowance for the finite diffraction beam width of the telescopes, which is 3″.0 FWHM (the 1.65 m parabola is underilluminated in these observations).

Table 1 gives values for the parameters R_C, τ, and α which best fit observations at maximum and minimum luminosities as shown in the theoretical curves of Figure 2, and the resulting dust temperatures at the inner radii R_C. These assume a distance to the star of 300 pc and luminosities $4.2 \times 10^4\ L_\odot$ and $2.1 \times 10^4\ L_\odot$, somewhat less than those in 1983 (Ridgway and Keady 1988). No precise measurement of the 11.15 μm flux during the 1988 maximum is available to compare with the calculated value of 60,700 Jy, but this is close to values generally found near other maxima of the source.

The optical depths in Table 1, determined from fitting our visibilities, agree well with determinations from other wavelengths, which range from ~0.4 to > 1.0 (Le Bertre 1987, 1988; Ridgway and Keady 1988; Martin and Rogers 1987; McCarthy, Howell, and Low 1980). Also, values of τ outside this range combined with the constraints mentioned do not allow good fits to the visibility curves. For $\phi \approx 0$ an inner radius $R_C = 0''.06$ is obtained (Table 1), which with the given luminosity requires a temperature of about 1350 K at R_C. This inner radius is 3 times the 0″.02 radius generally assumed for the star. At $\phi = 0$ this stellar radius implies an effective stellar temperature of 2300 K. The present data, including the visibility change with phase, are not consistent with $R_C \gtrsim 0''.08$ or $R_C \lesssim 0''.04$. Hence the temperature of dust formation must lie between about 1200 and 1600 K, with values in Table 1 being the most probable from present data.

TABLE 1

DUST SHELL PARAMETERS FOR IRC +10216 FROM VISIBILITY CURVES WITH CONSTRAINTS GIVEN IN THE TEXT

ϕ[a]	R_C[b]	τ[c]	α[d]	T_C[e] (K)	F_ν[f] (Jy)
0.0............	0″.06	0.80	0.36	1330	60,700
0.5............	0.05	0.96	0.44	1220	25,400

[a] Phase ϕ of the luminosity cycle.

[b] Dust shell inner radii R_C.

[c] Optical depth τ at 11.15 μm.

[d] Coefficient α for temperature distribution $T(r) \propto r^{-\alpha}$.

[e] Temperature T_C of dust at the inner radius.

[f] Flux F_ν at 11.15 μm.

Values of R_C and τ that fit visibilities at $\phi \approx 0$ also fit the values we obtain for $\phi \approx 0.35$, allowing only for the change in luminosity and using the same dust characteristics as at $\phi = 0$. The decreased luminosity cools off the dust shell, decreases intensities of the outer parts more than those of the inner parts, and thus increases visibility values by ~15% for those measured with the 4 m baseline. However, more striking changes in parameters are required to fit the visibility at minimum luminosity ($\phi = 0.5$). For this phase, the decreased luminosity alone, using the same dust parameters as for $\phi = 0$, raises the visibility values by less than half the observed change; other effects must be considered.

Velocities of the gas and dust allow motions of only about 0″.01 in 1 year's time and hence can be of importance to the observed change only in the innermost part where dust may be formed. Time constants are such that dust and radiation are essentially always in equilibrium. Cooling during minimum luminosity might allow more material to condense on dust grains, but any further condensation at mid- or outer radii of the dust shell would decrease the visibilities shown in Figure 2 rather than increase them. A substantial increase in 11 μm radiation is required close to the star relative to intensities further away to provide the enhancement of visibilities observed. This could occur by additional condensations on grains close to the inner radius, by formation of new dust inside this radius, or by a rapid decrease in temperature with radius (increase in α). Additional condensation on existing grains probably occurs to some extent, but a fit of the visibility curve near $\phi = 0.5$ requires dust at radii still smaller than the values of R_C found for $\phi = 0$. Table 1 gives the best-fitting value $R_C = 0''.05$ at $\phi \approx 0.5$ under the constraint that τ is proportional to R_C^{-1}. This again implies temperatures at the inner radius near 1300 K, but somewhat less than the optimum value for $\phi = 0$. Near $\phi = 0.5$, $R_C = 0''.04$ also fits the data, but with a somewhat worse χ^2 than $R_C = 0''.05$.

Variation of about 30% in the visibility of IRC +10216 between $\phi = 0$ and $\phi = 0.5$ has previously been found by McCarthy, Howell, and Low (1980) at 5 μm wavelength and attributed to a change in temperature of the dust. Calculations with our model indicate that indeed this magnitude of variation is expected from the change in temperature distribution and without a change in the inner radius; the enhanced change in visibility we find near $\phi = 0.50$ at 11 μm perhaps does not occur at 5 μm. A possible reason for this is discussed in the following section.

Clearly, simplified models often used to fit the visibilities need improvements as measurements become more precise and detailed. The increased steepness of the visibility curve observed for $\phi \approx 0.5$, for example, requires an increase in α; further refinements in the temperature variation with r would be desirable but probably do not substantially affect the conclusions here. Near the inner radius, R_C, variations in composition and in velocity from those of the shell at larger radii have not been allowed for, yet surely some occur. While the assumption of sphericity for the shell at 11 μm and the neglect of field rotation and polarization effects agree with best present observations, significant deviations from sphericity may be detectable. Clearly, further precision and refinements of the 11 μm visibilities are desirable.

V. DISCUSSION

Although some of the present results may be surprising in view of past observations and estimates, they appear consistent with theoretical expectations. In fact, there has been a longstanding theoretical puzzle (Tielens 1990*a*, *b*; Salpeter 1977) about why the dust appears to form only at the low temperatures near 1000 K previously estimated, and how the material can be transported to the rather large inner radii often estimated in the past without the prior formation of dust to provide radiation acceleration. Previous failure to find evidence of dust as near to the star as our data indicate is perhaps inherently connected with the lack of previous long-baseline interferometry on this object in the 10 μm wavelength region. The work of Sutton *et al.* (1979) involved a baseline of 5.5 m and agrees well with present measurements, but the leveling off of visibility values with resolutions in the range 4–5 × 10^5 rad^{-1} suggested no further dust to be resolved and a visibility for the star itself of about 0.10, which now with a 13 m baseline is shown to be $\lesssim$0.03. Work based primarily on interferometry or spectra in the 1–5 μm region of the infrared have indicated values of R_C between about 0″.09 and 0″.16 (Ridgway and Keady 1988; Le Bertre 1988; Haniff *et al.* 1990; Rowan-Robinson *et al.* 1986). This can be understood if the innermost dust grains are rather pure aluminum oxide, silicates, silicon carbide, or small ($\lesssim$50 Å) particles of amorphous carbon. These particles may have escaped detection because they are rather transparent in the near-infrared. However, they are strongly absorbing in the mid-infrared, and their formation is expected at temperatures near 1400 K or possibly above (cf. Tielens 1990), in reasonable agreement with temperatures indicated by the present models. Temperatures at the inner radii given in Table 1 are of course those at which densities are high enough to be easily detected rather than where nucleation may begin. As the particles move further from the star and cool, they may pick up impurities (Tielens 1990) and/or anneal (cf. Stencel *et al.* 1990) and thereafter absorb the near-infrared more strongly. Thus, if indications from past analyses of shorter IR measurements and from present results are both correct, one may conclude that particles which absorb at 11 μm but are poor absorbers for $\lambda \lesssim 5$ μm form at temperatures near 1300 K or possibly higher, later becoming more absorbing at $\lambda \lesssim 5$ μm when distances from the star have approximately doubled and temperatures dropped nearer to 1000 K. Furthermore, characteristics of the change in visibility with phase indicates that new dust forms during minimum luminosity, probably near the same high temperatures but in a region near the star where dust has not been able to form during the maximum luminosity period. Ridgway and Keady (1988) considered the possibility that R_C cycles with phase of the star but concluded that data available at the time provided no positive evidence for this. Most of the nucleation may occur near minimum luminosity, with particles then moving further away, possibly undergoing some evaporation by the time maximum luminosity occurs, and later some change in composition. It would be valuable to examine still more completely the variations with phase in IRC +10216 as well as the generality of this pattern and the associated dust parameters in a larger number and variety of stars.

VI. CONCLUSIONS

Measurements of interferometric visibilities of IRC +10216 in the 11 μm region show marked changes with phase and that the stellar disk contributes $\leq$0.03 to the visibility at this wavelength. Theoretical models of visibilities due to the dust shell appear to show that the dust forms at temperatures somewhat higher (1300–1500 K) and closer to the star than previously estimated. Furthermore, the variation with phase indicates that new dust is formed close to the star during minimum luminosity. These results are consistent with some theoretical expectations that small dust particles which absorb at 11 μm but are transparent at shorter wavelengths would form only a few stellar radii from the star and on moving to larger distances would cool, accumulating impurities and possibly annealing to become absorbing at shorter infrared wavelengths thereafter.

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