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DISTRIBUTION OF DUST ABOUT *o* CETI AND α ORIONIS BASED ON 11 MICRON SPATIAL INTERFEROMETRY

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ABSTRACT

Visibilities of *o* Ceti and α Orionis have been measured at a wavelength of 11 μm by a two-element heterodyne interferometer with maximum baseline spacings of 4 and 13 m. The measurements show that dust extends to within ~3 stellar radii of the oxygen-rich star *o* Ceti, the temperature there being near 1200 K. While the majority of dust near α Orionis is in a shell of inner radius 0".90, where the temperature is about 300 K, a region very near the star producing 11 μm radiation appears to be present. This may be represented as a stellar envelope of diameter 0".063 which is not transparent at 11 μm wavelengths.

Subject headings: infrared: sources — interferometry — stars: circumstellar shells — stars: diameters — stars: individual (*o* Ceti, α Orionis) — stars: mass loss

1. INTRODUCTION

The sizes of the well-known stars *o* Ceti and α Orionis and characteristics of their dust shells have already been much studied. We report new measurements of these objects, of particular importance in the region of a few stellar radii, obtained with a new two-telescope interferometer operating at high resolution in the 10 μm wavelength region. Dust is shown to form within about 3 stellar radii of *o* Ceti and at a temperature of about 1200 K, at a smaller radius and a higher temperature than earlier observations indicated, but in agreement with theoretical expectations. The primary dust shell around α Orionis has an inner radius of 0".90 and a temperature near 300 K. Some past observations have indicated dust may exist very close to the star and have given wide variations in the stellar diameter. Present measurements provide evidence for 11 μm–emitting material—possibly an extended atmosphere or possibly dust—very close to the star and at a relatively high temperature. These measurements reinforce earlier suggestions that a simple disk is not an adequate representation of the stellar intensity distribution.

2. OBSERVATIONS

The Infrared Spatial Interferometer (ISI), currently operating on Mount Wilson, contains two movable 1.65 m aperture telescopes and includes heterodyne detection, a microwave delay line, and lobe rotation (Bester et al. 1989; Bester, Danchi, & Townes 1990; Danchi et al. 1990). Figure 1 shows the power spectrum of a fringe due to α Orionis, fixed at 10 Hz by lobe rotation. The fringe visibility squared is proportional to the ratio of the total power in the fringe to the product of the total flux in each telescope. Thus the fringe power includes the power in the sidebands produced by atmospheric fluctuations as shown in Figure 1. Only a stellar wavefront coherent with the local oscillator wavefront is detected in each telescope, and both total flux and interference fringe power are derived from these two coherent waves. The resulting visibility measurement is in principle rather insensitive to atmospheric turbulence. For the measurements reported here, the projected baseline varied between ~2 and 13 m, providing spatial frequencies from $\sim 1.5 \times 10^5$ to 11.8×10^5 rad^{-1}, or resolutions between about 0".5 and 0".07. For the shorter baselines (≤4 m), the two telescopes were aligned east-west; otherwise, they were at an angle of 22° from the east-west direction.

Measurements were made during 1988, 1989, and 1990 on *o* Ceti and α Orionis. For *o* Ceti, Figure 2 shows visibilities measured at phases between $\phi = 0.96$ and 0.15 near maximum luminosity in 1989. The figure includes data taken by Sutton et al. in 1978 at $\phi = 0.11$ with a prototype of the present interferometer. Figure 3 gives a curve of visibility data for α Orionis. Lower resolution points ($< 6 \times 10^5$ rad^{-1}) were obtained between 1988 October and 1989 October and the higher resolution ones between 1989 November and 1990 August. Visibilities were calibrated from observations of α Tauri, assuming it is a point source, and at the shorter baselines, also from observations of α Herculis, assuming it is effectively a point source for baselines ≲4 m (cf. Sutton 1979; Danchi et al. 1990). Visibilities for α Orionis agree within probable errors with those of Sutton et al. (1977) for their baselines (≲5.5 m); these points as well as visibility measurements of Howell, McCarthy, & Low (1981) at very short baselines are shown in Figure 3.

3. DISCUSSION

3.1. *o Ceti*

Many interferometric studies of *o* Ceti have been carried out at visible and infrared wavelengths, though only a few at wavelengths as long as 11 μm (cf. Bonneau et al. 1982; McCarthy, Howell, & Low 1978; Sutton et al. 1978). Stellar diameters obtained in the visible region range from about ~0".030 to ≳0".100. The values obtained depend strongly on wavelength, being much affected by TiO absorption. For wavelengths outside the TiO region, a diameter of about 0".040 is typical (Labeyrie et al. 1977; Bonneau et al. 1982).

The dust shell around *o* Ceti appears to be resolved at the highest resolution shown in Figure 2. A total 11 μm flux of 4544 Jy was measured with the United Kingdom Infrared Tele-

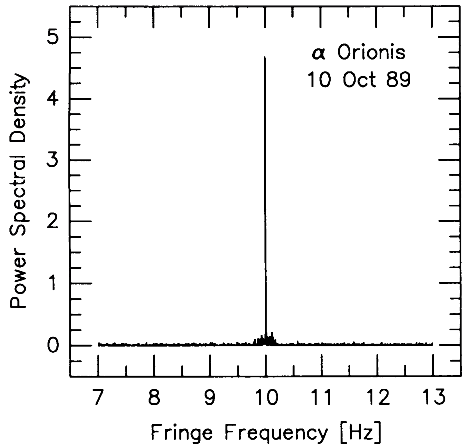

FIG. 1.—Power spectrum of interference fringes of α Orionis, taken on 1989 October 10. This fringe spectrum represents 5.5 minutes of observation and is kept at 10 Hz by lobe rotation. The central spike has a frequency width equal to the inverse of the observing time, or 3.0 mHz; sidebands are due to atmospheric fluctuations.

scope (UKIRT) atop Mauna Kea on 1989 October 30, and since a stellar visibility of about 0.17 is indicated by the curve of Figure 2, the flux from the stellar disk alone is 772 Jy. Combining this flux with a bolometric magnitude $m_{\rm bol} = 0.1$ (Robertson & Feast 1981) gives *o* Ceti an effective temperature of 2850 K and an angular diameter of 0".0336. This model assumes a spherical blackbody, which may be rather different from the case of a pulsating Mira star (cf. Beach, Willson, & Bowen 1988). It also assumes the star is not resolved at the 13 m baseline. We use this diameter and temperature, with a distribution of surrounding dust, as one appropriate model to fit the observed visibility curve, as shown in Figure 2.

The dust shell surrounding *o* Ceti is modeled by a density distribution proportional to r^{-2} (where *r* is the distance from

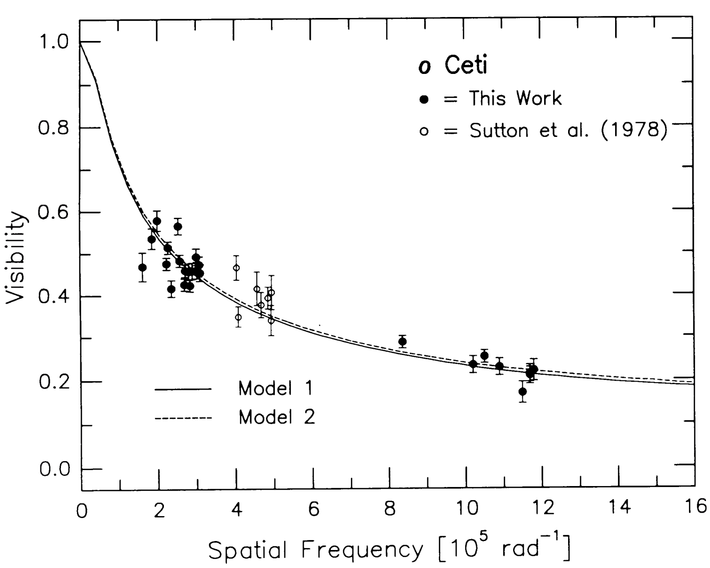

FIG. 2.—Visibilities of *o* Ceti as a function of spatial frequency near maximum of the LPV's luminosity cycle. The data include our measurements made between 1989 October 10 and December 5 and, in the spatial frequency range 4–5 × 10^5 rad^{-1}, data of Sutton et al. (1978) taken near maximum luminosity in 1978 January. The solid curve represents predictions from model 1 of Table 1 and the dashed curve those from model 2; both are acceptable fits to the data.

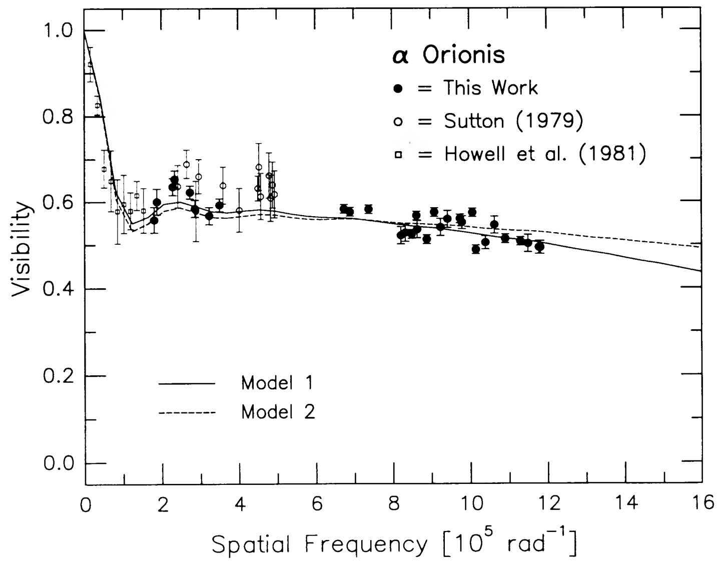

FIG. 3.—Visibilities of α Orionis as a function of spatial frequency. Filled circles display data measured with the ISI in 1988 October, 1989 October–December, and in 1990 August. Also shown are data of Howell et al. (1981) at low spatial frequencies, measured at 11.6 μm, and data of Sutton (1979), measured at 11.1 μm. Note the bump near 2.5 × 10^5 rad^{-1}. The solid curve represents predictions from model 1 of Table 1 and the dashed curve those from model 2. χ^2 for the preferred model 1 is one-half that for model 2.

the star), an inner radius R_C for the dust distribution, and a dust temperature which is in equilibrium with the radiation and proportional to $r^{-\alpha}$, where α depends on the wavelength dependence of absorption. For absorption proportional to λ^{-n}, $\alpha = 2/(4 + n)$ (cf. Danchi et al. 1990). The radiative transfer is approximated on the basis of an optically thin dust shell. This approximation tends to minimize the temperature of the inner edge of the dust distribution, but since the optical depth of the dust at 11 μm is only about 0.07, any error should not be large. Model 1 of Table 1 gives the parameters of such a dust shell and stellar disk which provide an optimum fit to the visibility curve, a bolometric magnitude $m_{\rm bol} = 0.1$, and approximately the observed 11 μm flux. The fit to the data is shown by the solid line in Figure 2. The inner dust radius of 0".05 which has been obtained implies a dust temperature there of about 1200 K. As was previously found for the carbon star IRC +10216 (Danchi et al. 1990), dust appears to be formed at a smaller radius and higher temperature than indicated by earlier measurements (Sutton et al. 1978). This result comes from the availability of longer baselines provided by the new mid-infrared interferometer we have constructed. Our measured visibilities of *o* Ceti agree well with those of Sutton et al. (1978) at baselines up to 5.5 m, but show a substantial decrease at longer baselines, thus demonstrating the presence of dust at smaller radial distances from the star than was previously suggested, but in agreement with theoretical models of the star by Bowen (1988). Initial dust nucleation may occur still closer to the star; we measure the radius where condensation is extensive enough to produce emission important at 11 μm. Dust of small radii cannot be measured with certainty at wavelengths shorter than about 5 μm because at such wavelengths it is probably transparent. Formation of dust close to stars and at temperatures near 1300–1500 K has for some time been expected from theoretical considerations (cf. Salpeter 1977; Tielens 1990), and formation of dust in the laboratory under somewhat similar conditions has been demonstrated (Frenklach, Carmer, & Feigelson 1989). It appears to occur both about the oxygen-rich star *o* Ceti, presumably in the form of silicates or aluminum oxide, as well as around IRC +10216 (Danchi et al. 1990), presumably in the form of amorphous carbon particles or carbon compounds.

An alternative model assumes the star itself is large enough to be partially resolved at the higher resolutions of Figure 2 and the inner radius for the dust is somewhat larger than the radius obtained above. Such a model may be appropriate since *o* Ceti is expected to have an extended atmosphere, though it is not clear that such an atmosphere would emit much 11 μm radiation. A model with an 11 μm diameter for the stellar disk of 0\".063, the same total luminosity, and an inner radius of the dust shell of 0\".07 at a temperature of 990 K does fit the visibility curve adequately, as shown by the dashed line in Figure 2. However, this case (model 2, Table 1) requires the very low temperature of 1360 K for the 11 μm stellar radiation, while at shorter wavelengths the temperature must be much higher to provide the observed luminosity. Even in this case, the inner radius of the surrounding dust shell must be as small as about 2 stellar radii, with a temperature as high as about 1000 K.

Variations in the visibility of *o* Ceti's dust shell with luminosity phase have been previously reported (Sutton et al. 1978; McCarthy et al. 1978). We also observe such variations but are still accumulating data extensive enough to provide a useful new discussion; hence, we show data in Figure 2 for essentially only one phase.

3.2. *α Orionis*

Dust associated with *α* Orionis has a distribution markedly different from that around many other stars with dust shells. Some light scattering by dust near the star has been reported from interferometry at visible wavelengths (Roddier & Roddier 1983). However, most of the dust is located at the considerable distance of about 1\" from the star (Howell et al. 1981; Sutton et al. 1977), and its distribution is asymmetric (Bloemhof, Townes, & Vanderwyck 1984; Bloemhof, Danchi, & Townes 1985). Emission is apparently episodic and associated with unusual surface disturbances (Karovska, Nisenson, & Noyes 1986). The visibility curve for *α* Orionis, Figure 3, is nevertheless fitted by an idealized spherically symmetric model of a dust shell of the same type used for *o* Ceti. This simplifed model is used because visibilities with a sufficiently large number of baseline directions have not yet been obtained to justify a more complex one, and the model allows useful parameters to be determined.

The visibility curve of *α* Orionis, including our data and those of Sutton (1979) and Howell et al. (1981), is well fitted with an optically thin dust shell ($\tau = 0.042$ from Table 1) with an inner radius $R_C = 0\overset{''}{.}90$ ($\gtrsim 30R_*$). This radius is in excellent agreement with measurements made by a linear array of detectors (Bloemhof et al. 1984). The most immediately striking feature of the visibility curve is a bump at a spatial frequency near 2.5×10^5 rad^{-1}. At this spatial frequency, the warm inner edge of the dust shell is just one fringe wavelength from the center of the star, so their intensities interfere constructively and produce a maximum, allowing the inner radius to be determined to a precision of ±0\".05. Although the model used was spherically symmetric and the bump in visibility accurately locates the inner edge of such a distribution, there is no requirement that the shell have such complete symmetry, and other measurements (cf. Bloemhof et al. 1984) indicate it does not. The observed bump is noticeably higher and sharper than that of the calculated curves. This can result from a more concentrated or lumpy distribution of the dust cloud. Thus, a reasonable fraction of the dust may be concentrated at a distance 0\".90 from the star, although more visibility measurements are needed to confirm this. Bernat et al. (1979) have detected absorption from CO in the direction of *α* Orionis of column density and temperature (200–270 K) which correspond well with the amount and temperature of dust in this shell. Since the CO velocity was found to be 11 km s^{-1}, it appears that *α* Orionis emitted an outburst of gas and dust about 100 yr ago, assuming a distance of 200 pc, and has been more quiescent since then.

The diameter of *α* Orionis's stellar disk has been measured many times since the famous first measurement of Michelson and Pease (1921) (cf. Balega et al. 1982; White 1980; Cheng et al. 1986; Buscher et al. 1990). Values are usually given for an equivalent uniform disk without corrections for limb darkening which, for measurements made in the visible region, should add about 10% to the star's actual diameter (Manduca 1979). At 11 μm corrections due to limb darkening are 1% or less. Cheng et al. (1986) fit speckle observations to a limb-darkened disk of ∼0\".065 diameter, or to a uniform disk of 0\".047 diameter plus a substantial flux from an envelope extending to a diameter as large as 0\".20. Recent interferometry at visible wavelengths by Buscher et al. (1990) shows an interesting irregularity on the stellar disk of about 15% the total stellar intensity and gives a disk diameter of 0\".057, uncorrected for limb darkening. This implies a diameter of 0\".063 after a limb-darkening correction. Christou, Hebden, & Hege (1988) fit their interferometric results to a Gaussian stellar intensity with full width at half-maximum of 0\".0396. Mozurkewich et al. (1990) obtain results that fit either such a distribution or a uniform disk of diameter 0\".0494. These varied results, plus other anomalies in the diameter of *α* Orionis (cf. Cheng et al. 1986), indicate that *α* Orionis may not be well represented by a circular disk of uniform intensity.

The total 11 μm flux of *α* Orionis measured with the UKIRT was 4270 Jy at the same time that visibility measurements indicated 60% of the 11 μm flux or 2560 Jy was due to the star. This, combined with a total stellar intensity of 1.104×10^{-4} ergs cm^{-2} s^{-1} (White 1980) at Earth, provides another measure of the stellar temperature and diameter, assuming a uniform disk. The result for a blackbody is a diameter of 0\".0464 and temperature of 3530 K, values which agree reasonably with a number of previous estimates. However, the visibility curve in Figure 3 indicates that the star is beginning to be resolved at spatial frequencies in the range 8–13 × 10^5 rad^{-1}, and the best fit to these observations requires a diameter of 0\".063, as indicated in Table 1. While this diameter agrees with Buscher et al. (1990), most measurements have yielded a significantly smaller diameter. The best fit of visibility measurements for the smaller disk diameter of 0\".045 and no dust closer than 0\".9 is model 2 of Table 1 and Figure 3. This model provides at best a χ^2 twice that of model 1, involving a larger disk, and hence is probably not acceptable. Each model assumes that the observed total luminosity illuminates the surrounding dust. However, it should be noted that the measured 11 μm flux gives the low temperature of 2240 K for a stellar disk of diameter 0\".063, and if this disk were black, its total luminosity would be only 0.3 that observed. Hence such a simple disk is not an adequate representation of the star, as has been emphasized by Scholz & Tsuji (1984) and Scholz (1985) on theoretical

TABLE 1

Parameters for *o* Ceti and α Orionis

Object	R_*[a]	T_*[b] (K)	R_C[c]	α[d]	T_C[e] (K)	τ_{11}[f]	F_{11}[g] (Jy)
o Ceti:							
Model 1.........	0″.0168	2850	0″.05	0.36	1170	0.067	4520
Model 2.........	0.0315	1360	0.07	0.36	990	0.054	4490
α Orionis:							
Model 1.........	0.0315	2240	0.90	0.40	296	0.042	4230
Model 2.........	0.0225	3580	0.90	0.40	296	0.043	4130

[a] Stellar radius R_*.
[b] Stellar temperature T_*, as measured at 11 μm.
[c] Dust shell inner radius R_C.
[d] Exponent α for temperature law $T(r) \propto r^{-\alpha}$.
[e] Temperature T_C of dust at the inner radius.
[f] Optical depth τ_{11} at 11.15 μm.
[g] Total flux F_{11} at 11.15 μm.

bases. Although measurements at longer baselines will resolve the star, and will be made later, we know of no artifacts that should invalidate the presently observed decrease in visibility at high resolutions. We must consider explanations other than resolution of a stellar disk of uniform temperature.

Roddier & Roddier (1983) reported dust within a distance 1–1.5 stellar radii of the stellar disk which 15 months later was found by Karovska (1984) to be expanded and weaker; Mékarnia, Gay, & Lefèvre (1990) also suggest the presence of dust near the star. As noted by Roddier & Roddier (1985) and discussed more fully in connection with dust close to IRC +10216 by Danchi et al. (1990), newly formed dust would scatter rather than absorb radiation of wavelengths shorter than a few microns. At wavelengths of 5 μm and longer, dust should emit strongly and thus may be much cooler than the ~2400 or ~2000 K expected for completely black dust as close as 0.5 or 1 stellar radius, respectively, from the stellar disk. For condensation, the temperature would need to be as low as about 1600 K.

Explanations of the apparent large stellar size which need consideration include the following:

1. A small dust shell as close as about 1 stellar radius: Dust formation close to α Orionis has been previously discussed, for example, by Tsuji (1979). Draine (1981) has estimated that dust may condense no closer than 1.8 stellar radii. This is almost close enough to produce the present results, as well as to explain the large sizes of envelopes sometimes reported for α Orionis from visual observations. However, such a model does not fit present observations, since the 11 μm intensity requires a temperature of 2240 K for material within a diameter of 0″.063, and this makes condensation unreasonable regardless of favorable radiation characteristics. Perhaps a more complex dust model could adequately fit present data. The particles would need to be small (e.g., $\lesssim 50$ Å) to not scatter too much visible light.

2. Some small dust clouds, not necessarily near the star, which are being resolved at high resolution: We found no small dust cloud model which can fit all the observed conditions, and this explanation hence seems unlikely.

3. Resolution of the separation between α Orionis and one of the two stars reported very close to it (Karovska et al. 1986): However, the brightest one of these is estimated to be 3.6 mag less than α Orionis; its intensity would be too weak to produce the decrease in visibility seen.

4. An inflated atmosphere around the star which emits 11 μm radiation but is less emissive at visible wavelengths: Mechanical forces exist which extend the atmosphere of supergiants considerably beyond the steady state distribution. These forces also induce mass loss and produce chromospheric gas moving both away and toward the star, sometimes at high velocities (cf. Deutsch 1960). For α Orionis in particular, a cycling of radial velocities of such material has been well demonstrated by Smith, Patten, & Goldberg (1989). However, no spectral lines that absorb the narrow-band (0.1 cm^{-1}) 11.15 μm radiation used for these measurements are known, although the spectrum of H_2O in highly excited states is not well enough known to rule it out completely. Sufficiently intense free-free emission of 11 μm radiation by ionized material in an inflated atmosphere seems unlikely from known measurements (Skinner & Whitmore 1987) of free-free emission of α Orionis in the microwave region.

Thus present models of α Orionis do not provide a natural explanation of the apparent decrease in visibility observed toward high spatial resolutions.

4. CONCLUSIONS

The visibility curve obtained at 11 μm for the oxygen-rich star *o* Ceti at relatively long (13 m) baselines makes it clear that dust is formed close to the star ($\sim 3R_*$) and at a relatively high temperature ($\gtrsim 1200$ K). Such behavior has also been observed in the carbon star IRC +10216. For α Orionis a rather large inner radius (0″.9 ± 0″.05) is obtained, and relatively little dust is present at smaller radii. However, the observed decrease in visibility at the largest baselines shows that either the atmosphere is quite extended and somewhat opaque to 11 μm radiation at diameters as large as 0″.063 or there is a small amount of fine dust very near the star.

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