LONG BASELINE INTERFEROMETRIC OBSERVATIONS OF CIRCUMSTELLAR DUST SHELLS AT 11 MICRONS

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Abstract. The spatial distribution of dust around a sample of well-known late-type stars has been studied with the Infrared Spatial Interferometer (ISI) located at Mt. Wilson. Currently operating with a single baseline as a heterodyne interferometer at 11.15 μm, the ISI has obtained visibility curves of these stars. Radiative transfer modeling of the visibility curves has yielded estimates of the inner radii of the dust shells, the optical depth at 11 μm, and the temperature of the dust at the inner radii. For stars in which the dust is resolved, estimates of the stellar diameter and temperature can also be made. Broadly speaking two classes of stars have been found. One class has inner radii of their dust shells very close to the photospheres of the stars themselves (3-5 stellar radii) and at a higher temperature ($\sim$ 1200 K) than previously measured. This class includes VY CMa, NML Tau, IRC +10216, and o Ceti. For the latter two the visibility curves change with the luminosity phase of the star and new dust appears to form at still smaller radii during minimum luminosity. The second class of stars has dust shells with substantially larger inner radii and very little dust close to the stars, and includes α Ori, α Sco, α Her, R Leo, and χ Cyg. This indicates sporadic production of dust and no dust formation within the last several decades.

Key words: Interferometry – Dust Formation – Variable Stars – Mass Loss

1. Introduction and Observations

As stars evolve off the main sequence of the Hertzprung-Russell (H-R) diagram and onto the asymptotic giant branch they begin to lose mass through a possible assortment of processes such as cool winds (Salpeter, 1974), thermal pulses (Schwarzschild and Härm, 1962) or other forms of mass ejection. High spatial resolution observations of the dust surrounding these stars is particularly helpful to the study of mass loss since relatively little is known about the physical conditions of the material from the photosphere out to about 10 stellar radii (R_*)(Lafon and Berruyer,1992).

The Infrared Spatial Interferometer (ISI) developed by our group at the University of California at Berkeley is being used to measure the spatial distribution of dust surrounding these stars. The ISI is a two-element heterodyne interferometer operating at 11.15 μm. Current baselines (4 m to 35 m) give spatial resolutions between ~600 and 33 mas. More detailed descriptions of the ISI system can be found in the papers by Townes et al. and by Bester et al. in these proceedings.

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Preliminary ISI observations of the carbon star IRC +10216 (cf. Danchi et al., 1990), and the oxygen-rich Mira variable, *o* Ceti (Bester et al., 1991) suggested that dust is formed rather close to the stars ($\leq 3\ R_*$), and at higher temperatures (~1200 K), than previously thought. Also new dust was created at still smaller radii during the minimum phase of the luminosity cycle. Observations of the M supergiant α Orionis showed that it had dust rather far from the star ($\sim 45\ R_*$) and at a much lower temperature (~300 K) than the other two stars, indicating sporadic production of dust. In this paper we present an overview of results on thirteen stars observed by the ISI and listed in Table I. The sources span a range of spectral types including early M supergiant stars such as α Ori and α Sco; two S stars, χ Cyg, and W Aql; the carbon star IRC +10216, and oxygen-rich Mira variables such as *o* Ceti and R Leo.

Many of the sources were observed with the ISI over a period of several years beginning in 1988 with a 4 m E-W baseline. However, the bulk of the data analyzed (summarized in Table I) were obtained in the late summer of 1992 with the 13 m baseline and early fall 1992 with the 10 m baseline. Considerable care was used to ensure that the data analyzed were at the same phase of the star even if the data were taken at different epochs. However, the visibility curves for *o* Ceti varied from epoch to epoch even at the same luminosity phase so that combining data from different epochs may be problematic. The squares of the fringe visibilities are obtained from the ratio of the power in the 10 Hz fringe signal to that of the product of the total signal power in each telescope as explained in Danchi et al. (1990). Calibration of the visibilities were obtained from α Tau and α Boo, which are point sources at the present baseline spacings. As a secondary standard α Ori was often used since its visibility curve has been measured quite accurately.

2. Models and Results

The inner radii of the dust shells were determined with the help of a radiative transfer model developed by Wolfire and Cassinelli (1986) for the study of massive protostars. This model assumes the dust shell is spherically symmetric and centered on the star, which is assumed to be a blackbody. If possible, the stellar temperature and diameter were taken from recent estimates from stellar interferometry. Otherwise, an effective temperature based on the spectral type at the minimum and maximum from the calibration of Dyck et al. (1974) was used. The diameter of the star could then be estimated from the visibility (for those stars where the dust was resolved) and the 11 μm flux determined by T. Geballe (1988-92) at the United Kingdom Infrared Telescope.

Optical properties of both silicate and graphite grains were taken from Draine and Lee (1984, 1987). Complex dielectric constants for amorphous carbon (AC and BE phases) were obtained from Rouleau and Martin (1991). The grains were assumed to have the Mathis, Rumpl and Nordsieck (1977) ($a^{-3.5}$) size distribution, varying from a radius of 0.005 μm to 0.25 μm. The number of grains of a given size per hydrogen atom were taken from Draine and Lee (1984), which gives gas-to-dust ratios equal in value to the interstellar medium (i.e., $\sim$ 180 for silicates). The grain composition could be varied from pure silicates, graphites, or amorphous carbon, to mixtures of any two of the three possibilities. The dust composition and gas-to-dust ratio are assumed to have a constant radial dependence.

The density of dust was assumed to have a power-law radial dependence at large distances from the inner edge of the dust shell, usually r^{-2}; although $r^{-1.5}$ was used for IRC +10216. Near the inner edge of the dust shell, radiative acceleration of the dust gives a density distribution more strongly peaked than a simple r^{-2} model. This effect is modeled by a density distribution like that of Schutte and Tielens (1989), which peaks above the r^{-2} law at the inner radius and smoothly joins the r^{-2} distribution at a few times the inner radius. No dust is assumed between the photosphere and the inner radius as well as beyond the outer radius, usually 2.5″.

Once the above parameters were determined an inner radius of the dust shell was chosen and the gas density was adjusted to give the optimum fit to the visibility curve. The 11 μm flux from the model was also compared to that observed by Geballe at an epoch near that of the ISI observations. A new inner radius was chosen depending on the result of the previous computation. The model spectrum could also be compared to the IRAS Low Resolution Spectrometer spectrum and changes in the dust composition could be made to improve the agreement between the two spectra. Detailed agreement may not be possible because the IRAS spectra were taken with a very large aperture ($\sim 5' \times 6'$) compared to that of the model spectra ($\sim 5''$).

Table I summarizes the results of the model fitting procedures. The spectral type is displayed in column 2; the phase in column 3; the inner radius of the dust shell, R_{in}, in column 4; the inner radius normalized to the stellar radius, R_{in}/R_*, in column 5; the temperature at the inner radius, T_{in}, in column 6; and the 11 μm optical depth from the outer radius to the inner radius along the line-of-sight to the star, τ_{11}, in column 7. The presence or absence of SiO, H_2O, and OH maser emission (cf. Benson et al., 1990) are noted in columns 8, 9, and 10 respectively.

It is clear from Table I that the stars can be divided into two classes: those with dust close to the star and those with dust far from the star (i.e., $\geq 8\ R_*$). Stars without SiO maser emission are M supergiants of the earliest spectral types; however, the two S stars do produce SiO masers, which suggests their atmospheres may be more dynamic and extended than the M supergiants. This is consistent with the light curves. For example, the light curves of the M supergiants vary irregularly with small amplitudes ($\sim 1m_V$), while those of the S stars vary regularly with a quasi-sinusoidal shape, with amplitudes up to $\sim 8m_V$. Neither the early M supergiants nor the S stars have H_2O or OH masers. An apparent anomaly is U Ori, a Mira variable of period 368 days, having all three masers. In this case, the absence of dust close to the star may be an artifact of the presently attained resolution, which is insufficient to rule out dust closer to the star.

The remainder of the stars have dust rather close to the star; the mean distance is $3.9 \pm 1.6\ R_*$, less than half the distance than previously thought, when it was believed dust formed at $\sim 10\ R_*$ (Hinkle et al., 1982). Most all of these stars have all three masers unlike the stars with dust farther from the star. It is difficult to generalize about the relationship to the light curves, except that for the Miras R Leo and *o* Ceti, the light curves are more asymmetric (i.e., sawtooth shaped) than the S stars. However, the longer period stars, for example VY CMa and VX Sgr,

TABLE I
Inner Radii of Dust Shells of Recently Observed Stars

Star	Spectral Type	Phase	R_{in} $''$	R_{in}/R_*	T_{in} K	τ_{11}	Maser SiO	Maser H_2O	Maser OH
Dust far from star									
α Sco	M1.5I		1.0	52	320	1.1(-2)	N	N	N
α Ori	M1-M2I		1.0	46	400	6.5(-3)	N	N	N
α Her	M5I		0.25	18	520	1.6(-2)	N	N	N
χ Cyg	S10	min	0.30	18	410	5.7(-2)	Y	N	N
U Ori	M6	max	0.08	11	540	9.2(-2)	Y	Y	Y
W Aql	S3	max	0.07	8.1	1100	7.8(-2)	Y	N	N
Dust close to star									
IRC +10216	C9	max	0.09	2.4	1360	1.2(-0)	Y	N	N
		min	0.07	1.9	1030	1.4(-0)			
R Leo	M9.5III	min	0.07	2.7	790	1.0(-1)	Y	Y	Y
o Ceti	M7III	max	0.06	3.0	1280	1.4(-1)	Y	Y	N
		min	0.06	3.0	1060	1.4(-1)			
VX Sgr	M10I	min	0.06	4.6	720	5.6(-1)	Y	Y	Y
VY CMa	M5(C6)I	max	0.05	5.3	1560	2.9(-0)	Y	Y	Y
		min	0.04	4.2	1360	2.9(-0)			
NML Tau	M6	max	0.05	5.5	990	1.7(-0)	Y	Y	Y
R Aqr	M8.5	min	0.07	6.8	530	2.3(-1)	Y	N	N

have either irregular quasi-sinusoidal or sinusoidal shapes, respectively.

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