THE ASTROPHYSICAL JOURNAL, 463:336–343, 1996 May 20

MEASUREMENT AT 11 MICRON WAVELENGTHS OF THE DIAMETERS OF α ORIONIS AND α SCORPII, AND CHANGES IN EFFECTIVE TEMPERATURE OF α ORIONIS AND VERY RECENT DUST EMISSION

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Received 1995 October 16; accepted 1995 December 4

ABSTRACT

The angular diameters of the stellar disks of α Ori and α Sco have been determined to be 56.6 ± 1 and 44.4 ± 2 mas, respectively, at 11 μm using long-baseline interferometry. These values are about 10% larger than the most reliable diameters determined at visible wavelengths, and are consistent with predictions of significant visible limb darkening, but only minor infrared limb darkening. Variations in temperature and luminosity of α Ori during 1989–1995 have been studied by a combination of interferometry, optical photometry, and spectrophotometry. This shows that observed variations in m_v are primarily due to temperature changes. A recent episode of dust formation at about 0."1 from the star has been detected; it is probably the result of a discrete mass-loss event of modest size.

Subject headings: dust, extinction — infrared: stars — stars: fundamental parameters — stars: individual (α Orionis, α Scorpii) — techniques: interferometric

1. INTRODUCTION

Asymptotic giant branch (AGB) stars enrich the interstellar medium through cool dust outflows or winds. In addition, they are interesting theoretically and observationally because they display a complex set of phenomena including pulsation, dust, and molecule formation, and exhibit SiO, OH, and H_2O maser activity (see Diamond et al. 1994; Bowers, Johnston, & de Vogt 1989; and Lane et al. 1987, respectively). Despite considerable theoretical and observational work, the details of the origins of the winds remain uncertain (see Lafon & Berruyer 1991). A promising scenario for the formation of the winds involves stellar pulsation, which causes the atmospheres of these stars to be extended far beyond that expected for static atmospheres. This allows the gas to be cool and dense enough to condense dust. Radiation pressure drives the dust, and in turn the dust drags along the gas creating the observed outflows (Bowen 1988; see Hearn 1990 for a review). A number of other scenarios exist that could also drive the outflows, such as Alfvén (Holzer, Fla, & Leer 1983) and acoustic waves (Pijpers & Habing 1989). Observational parameters that are fundamental to all such theories include the diameters of the stars and the atmospheric scale heights.

Although stellar diameters have been measured using spatial interferometry for the early spectral types (see Quirrenbach et al. 1993 and references therein), much less work has been done on late M stars having significant dust shells. This is due to the fact that most prior work has been at optical wavelengths. In the past few years, however, the observational picture has improved because long-baseline interferometers for the near- and midinfrared have developed to the point where they are being used for regular observations. The recent review by Danchi & Bester (1995) discusses the status and results of long-baseline interferometers at optical and infrared wavelengths.

This paper presents the first interferometric measurements of stellar diameters in the midinfrared (11 μm), those of α Orionis and α Scorpii. These were made with the infrared spatial interferometer (ISI) on Mount Wilson (Bester, Danchi, & Townes 1990; Bester et al. 1992). A burst of dust formation near α Ori in late 1994 is also indicated by the observations.

The midinfrared is a particularly suitable wavelength for measurements of diameters of late-type stars because (1) limb darkening is estimated to reduce the apparent stellar diameter no more than about 1%, as compared with about 10% in the visible region (Ridgway, Wells, & Joyce 1977; Scholz & Takeda 1987), (2) bright spots due to temperature variations on the stellar disks do not distort the uniformity of the brightness of the stellar disk as much as in the visible region, and (3) the longer wavelengths are less susceptible to scattering by circumstellar dust, which can produce an apparent enlargement of the sizes of stars having dust shells (Tsuji 1978). As expected from limb darkening and bright spots, the measured midinfrared diameters of the two stars, α Ori and α Sco, are somewhat larger than apparent values obtained at visible wavelengths. The measurements also show that the typical variations which are observed in the visible brightness of α Ori are largely due to changes in surface temperature rather than in size. However, a sharp decrease in visible brightness in α Ori in late 1994 appears to be associated with very recent dust formation.

The first star to be measured by stellar interferometry was α Ori (Michelson & Pease 1921), and this first measurement

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gave a diameter of 47 mas with an estimated precision of 10%. Since then, many measurements have been reported. White (1980) summarized data as of 1980 and deduced an average diameter of 44 mas and cyclic changes of ± 8 mas, with the apparent 5.8 yr period of visible magnitude variations reported by Sanford (1933) and others. Cheng et al. (1986) also summarized measured visible sizes, including new speckle measurements. Speckle measurements made by Cheng et al. indicated a complex brightness distribution not explainable by a uniform disk, and an indicated effective disk diameter of 42.1 ± 1.1 mas. Even prior to this, there had been indications of bright features on the stellar surface which could distort stellar size measurements. These were clearly demonstrated with nonredundant aperture masking of the 4.2 m Herschel telescope by Buscher et al. (1990). Tuthill (1994) made additional measurements of this type, which yielded closure phase results as well as visibilities. Allowing for localized bright features indicated by the measurements, he obtained a set of five diameter determinations at 700 nm. When added to two similar measurements made by Buscher et al. (1990) and Wilson et al. (1992), which are listed by Tuthill, these give a mean diameter of 52.7 ± 1.3 mas. If a uniform disk is assumed and the bright spots not allowed for, the much smaller value of 45.4 ± 1.2 mas is obtained (Tuthill 1994). This history shows that accurate measurements in the visible region of the star's diameter are difficult, although recent techniques to minimize their effects may obviate most of the problems associated with bright features.

Accurate measurements of α Ori's diameter at infrared wavelengths are in some ways easier than in the visible region, and a measurement has been made at 2.2 μm, for which a diameter (without allowance for limb darkening or nonuniformities) of 44.2 ± 0.2 mas was reported (Dyck et al. 1992). However, measurement of stellar size in the infrared can be complicated by the fact that some stars are surrounded by dust; interferometric measurements must resolve the dust and separate its radiation from that of the star. This is not in principle very difficult, since the dust does not normally form closer than a few stellar radii from the star. In particular, α Ori and α Sco have been shown to not have much dust closer to them than about 1″ (Danchi et al. 1994), indicating that they have not emitted much material recently. However, evidence for one very recent dust formation event near α Ori will be discussed below. For spatial resolutions which resolve the dust but not the star, the visibility value simply shows the fraction of radiation emitted by the star; higher resolutions yield smaller values of visibility as the star is resolved. If the stellar luminosity varies, then the fraction of radiation provided by the dust or star may change, varying the visibility value in a way that complicates the process of obtaining a reliable visibility curve. Fortunately, such variations are normally small enough to not produce major errors. In the case of α Ori and its dust shell, a variation in visible magnitude m_v of 0.5 due to a temperature change (which is a common occurrence for this star) changes the visibility value by about 0.05 when the dust shell but not the star is resolved. While not large, such a change can produce noticeable errors in determination of the stellar size if different parts of the visibility curve are measured at different times. The ISI has encountered this complication, since separation between the two telescopes has normally been constant for a few months before a major change in baseline is made.

2. OBSERVATIONS

The long-baseline interferometric observations reported here were made with the ISI on Mount Wilson, operating at 11.15 μm. It is a two-element interferometer comprised of movable 1.65 m aperture telescopes, with Pfund-type optics and heterodyne detection. With the present site layout, available baselines are between 4 and 35 m (Bester et al. 1990, 1992).

The visibility of α Ori measured in the period 1988–1992 at a wavelength of 11.15 μm has been previously reported (Bester et al. 1991; Danchi et al. 1994). In this paper, new visibility data taken in 1993–1994 and extending to much higher resolutions, so that the stellar disk is partly resolved, are presented. The 1993 observations were made on 13 nights from July through September with the 10 m baseline, and on six nights in October and November with the 32 m baseline, as shown in the journal of observations in Table 1. In 1994, α Ori was observed with a 32 m baseline on five nights in July and August, and with a 4 m baseline on 16 nights in September and October. Data on separate nights were averaged together, and the points shown are the mean values, while the error bars represent the standard deviations of the means. However, the 1993 data were processed separately from the 1994 data. Typically, six or so data points were averaged together, although in some cases there were as many as about 20 points averaged. Visibilities were calibrated relative to α Tau, a K5 giant having no dust emission.

Visibility data and models for α Sco were also previously published (Danchi et al. 1994). These models also indicated that the inner radius of the dust shell was approximately 1″ from the star, and that there was little dust between the star and the inner radius of the dust shell. Unlike α Ori, in α Sco there is no indication of recent dust formation as will be shown below. For α Sco, new data were obtained in 1993 on one night in July and three nights in August. In 1994, data were obtained on six nights in June, seven nights in July, and one night in August. The data for α Sco were processed in the same way as the data for α Ori; however, all of the data were used in the determination of the diameter.

Measurements of luminosities in the midinfrared were made with the United Kingdom Infrared Telescope (UKIRT) from 1989 to the present. Both narrowband photometry (using the single-channel bolometer in UKT8) and, more recently, 7–13 μm spectrophotometry (using the linear array spectrometer CGS3) have been employed, using 5″ diameter apertures and standard chopping and nodding techniques. Flux calibrations were derived from observations of α Lyrae, α Aurigae, and α CMa, and are believed to be accurate to ± 3% or less for all observations reported

TABLE 1

JOURNAL OF ISI OBSERVATIONS OF α ORI AND α SCO, 1993–1994

Object	Dates	Baseline (m)	Orientation
α Ori......	1993 Jul 27–Sep 30	9.6	N122°7 E
	1993 Oct 20–Nov 9	32	N118.4 E
	1994 Jul 27–Aug 19	32	N118.4 E
	1994 Sep 5–Oct 12	4	N 89.4 E
α Sco......	1993 Jul 16–Aug 19	9.6	N122.7 E
	1994 Jun 10–Aug 19	32	N118.4 E

TABLE 2

FLUX DENSITY OF α ORI AND α SCO AT 11.15 MICRONS

Date	α Ori (Jy)	α Sco (Jy)
1989 Nov 1	4274	...
1990 Aug 20	...	2694
1992 Aug 19	4702	2439
1993 Nov 20	4410	...
1994 Aug 26	4711	...
1994 Nov 20	4844	...
1994 Jan 14	4852	...
1995 Mar 17	4910	2631
1995 Aug 20	4869	2446

here. Wavelength calibration of the spectra was derived from the line emission of a krypton arc lamp observed in 4th, 5th, and 6th order. The spectra of α Ori and α Sco are dominated by strong absorption due to photospheric SiO at 7–9 μm and emission due to circumstellar silicate dust particles at 9–12 μm. Details of the spectral shape are least reliable near the peak of the silicate emission at 9.7 μm, due to strong telluric absorption of ozone near that wavelength. The flux densities in janskys at 11.15 μm, the wavelength at which the interferometer was operated, are listed in Table 2.

3. RESULTS AND DISCUSSION

3.1. *α Orionis*

3.1.1. *Possible Variations in Stellar Size*

An important question concerning the many measurements of the size of α Ori is whether there are in fact substantial changes in size—for example, with the observed changes in visible magnitude and the semiperiodic variations which have been indicated in some publications.

During the past few years, measurements of m_v by Krisciunas (1990, 1992, and 1994) and Luedeke (1995), combined with our own measurements of both the 11 μm intensity at the UKIRT telescope and the visibility curve by the ISI, allow a separate evaluation of the 11 μm fluxes from the dust and from the stellar disk. Hence, the relative changes in both visible light and 11 μm radiation from the star (as opposed to star plus dust) are available. From these, the effective changes in temperature and diameter can be separately evaluated if new dust formation does not produce new obscuration of the visible light. Figure 1 shows measured values of m_v and 11 μm fluxes between 1988 and 1995. From changes shown in this figure prior to late 1994 (Julian Day 2,449,700), it is immediately clear that most of the change in m_v is due to temperature variations. Visible brightness changes exponentially with stellar temperature, whereas 11 μm brightness changes approximately linearly, and observed changes in the visible before 1994 August are seen from this figure to be in the same direction but much larger than those at 11 μm. A variation in stellar size at constant temperature would change both wavelengths by the same factor.

Calculation provides a quantitative evaluation of possible size changes. As can be seen from Figure 1, m_v varies appreciably over rather short times. Some of these times are shorter than the period over which the present visibility curve has been measured using the ISI. Hence, the reality of such variations is both interesting in itself and important to the accuracy of the present size measurement. In Table 3, values of m_v for a given date are the averages of the six points closest in time or, in the case of 1992 August 19, an interpolation between the two points somewhat widely spaced on either side of that date. For the calculated values of other parameters, we assume a dust shell model previously developed from ISI measurements (Danchi et al. 1994), and from the model calculate the change in 11 μm

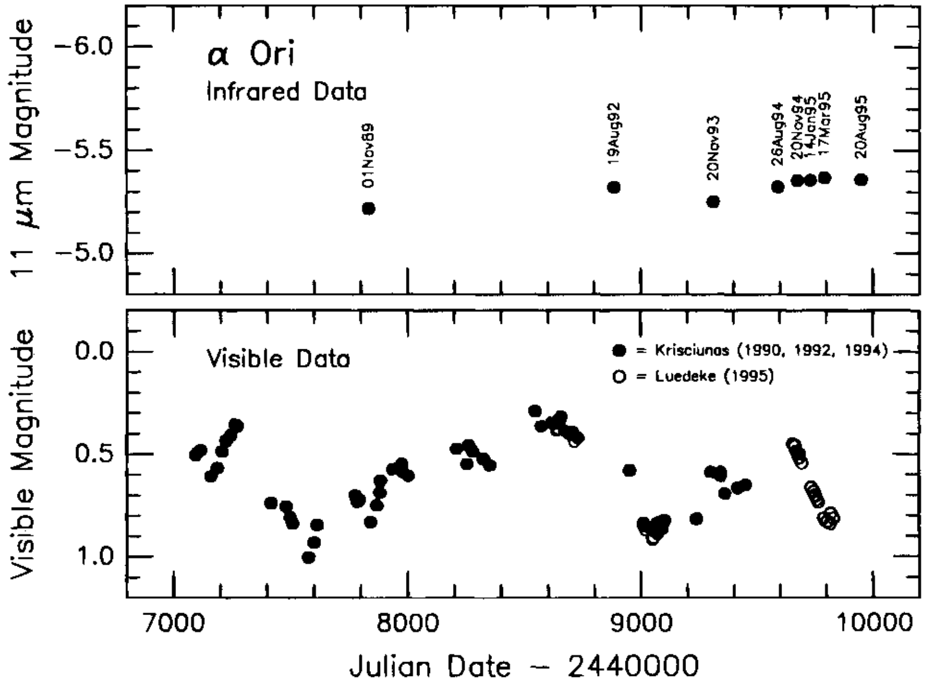

FIG. 1.—Visible and 11.15 μm magnitudes (m_v and $m_{11.15}$) of α Ori between JD 2,447,000 and JD 2,450,000 (1988–1995). For m_v, filled circles represent measurements by Krisciunas (1990, 1992, and 1994); open circles represent measurements by Luedeke (1995). The upper part of the figure gives 11.15 μm magnitudes, which clearly vary much less than m_v.

TABLE 3

SUMMARY OF APPARENT CHANGES IN TEMPERATURE AND AREA OF α ORI, 1989–1995

Date	Measured m_v	Ratio of Visible Flux to Standard	Stellar Temperature (K)	Stellar Area Relative to Standard	Dust Temperature (K)	Calculated 11.15 Micron Fluxes: Stellar (Jy)	Dust (Jy)	Total (Jy)	Measured 11.15 Micron Flux (Jy)
1989 Nov 1........	0.738	0.811	3555	0.963	385.4	2642	1628	4270	4274
1992 Aug 19[a]......	0.511	1.000	3640	1.000	402.0	2821	1881	4702	4702
1993 Nov 20	0.652	0.878	3589	0.973	391.0	2695	1710	4405	4410
1994 Aug 26	0.485	1.024	3654	0.996	402.7	2822	1892	4714	4711
1994 Nov 20	0.493	1.017	3635	1.027	406.8	2892	1957	4849	4844
1995 Jan 14	0.690	0.848	3521	1.082	404.4	2934	1919	4853	4852
1995 Mar 17	0.794	0.771	3459	1.124	405.0	2984	1929	4913	4910

[a] The standard.

radiation intensity of the dust shell due to change in stellar luminosity. The star is assumed to be a uniform disk of temperature 3640 K, surrounded by a dust shell of temperature of 402 K, on 1992 August 19, in accordance with this model. Changes in stellar temperatures and diameters are calculated for measurements on other dates on the basis of this model. The star as measured on 1992 August 19 is taken as a standard, and variations from this standard are given for times between 1989 November and 1995 March. Resulting calculated values of temperature and relative area of the star are given in Table 3. The variations are of primary interest here, and should not be very much affected by possible modest errors in the initial model or by simplified assumptions.

Table 3 is divided into two time periods. The first, from 1989 November to 1994 August, shows variations in visible brightness much greater than those in the stellar surface area. Visible flux varies 12% and 19% in two cases, largely due to temperature changes. The area varies by less than 4%, which may largely be due to measurement and model uncertainties. The second period, beginning in 1994 November, with particularly unusual results in 1995 January and March, indicates that a new phenomenon has appeared. The unusual behavior is clear from Figure 1, where, beginning in 1994 November, m_v drops sharply while the 11.15 μm flux stays constant or increases somewhat.

The visibility curve of 1988–1992 indicated no appreciable dust between the star and a radius of about 1″ (Danchi et al. 1994). The model resulting from these measurements is used in calculating the changes of temperature and area of the star given in Table 3. This table shows that, if no new dust is assumed, during the time from 1994 November 20 to 1995 March 17, the area of the star would have to increase by 10% and the temperature drop by about 200 K. This implies a steady expansion velocity of about 5 km s^{-1}. In fact, such an expansion probably does not occur; rather, there is evidence for the appearance of new dust, as will be discussed in § 4.

If the changes in m_v had come from a spot on the star covering only a fraction of the total area, which also changed in size proportionally to any total change in the disk area, the spot's temperature would have increased substantially more and the stellar diameter change would be somewhat different, but overall conclusions would be similar to those from the simpler model of Table 3. Although these disk diameter changes are not very precisely determined because the models and data are not precise, they do indicate clearly that during the first period of measurements the fractional diameter change is much smaller than the large variations indicated by some past measurements, and that the primary changes in m_v are associated with temperature variations or evolution of dust.

3.1.2. *Visibility Curve and Diameter*

The visibility of α Ori measured in the period 1988–1992 at a wavelength of 11.15 μm has been previously reported (Bester et al. 1991; Danchi et al. 1994). It was shown that there was a dust shell at a radius of about 1″ from the star with a rather sharp inner edge and very little dust between that radius and the star itself. New visibility data taken in 1993–1994, and extending to much higher resolutions so that the stellar disk is partly resolved, are shown in Figure 2.

The solid curve in Figure 2 for data of 1988–1992 is based on the best model fit from a previously published radiative transfer model of Danchi et al. (1994, Table 7 and Fig. 6 of that paper). However, at that time the dust shell was resolved, but not the star itself. Hence, a range of stellar diameters and temperatures could reasonably fit the measured luminosities and the visibility curve. The present model for Figure 2 differs from the previous one in that the star is larger and cooler than assumed earlier. Previously, the stellar diameter and temperature were 43.6 mas and 3500 K; the present model assumes they are 56 mas and 3190 K, respectively, which gives the correct total luminosity. In addition, the present model, which fits the recent data of 1994, includes a thin shell of dust at a radius of 0″1 from the center of the star. This is what makes the dashed curve of Figure 2 differ from the solid one, where no dust near the star is assumed. The inset in Figure 2 displays these two models and the data used in the previously published model (Danchi et al. 1994). Note the close agreement between the older data and the solid curve, as well as agreement of the new data with the dashed curve.

The fitting process began with the previously published model, and the 1993 data were used only to determine the stellar diameter. The stellar diameter (uniform disk) was chosen, and the optical depth was varied to minimize the χ^2 for that diameter. Successive diameters were tested, and 57 mas gave the global optimum fit. As can be seen in the figure, the agreement between data and model is best at the spatial frequencies accessed by the 10 m baseline near spatial frequencies of 6×10^5 rad^{-1} and by the 32 m baseline at spatial frequencies in the range 15–30 $\times 10^5$ rad^{-1}.

An independent calculation, which used only a uniform disk and fitted only the diameter and ratio of the stellar

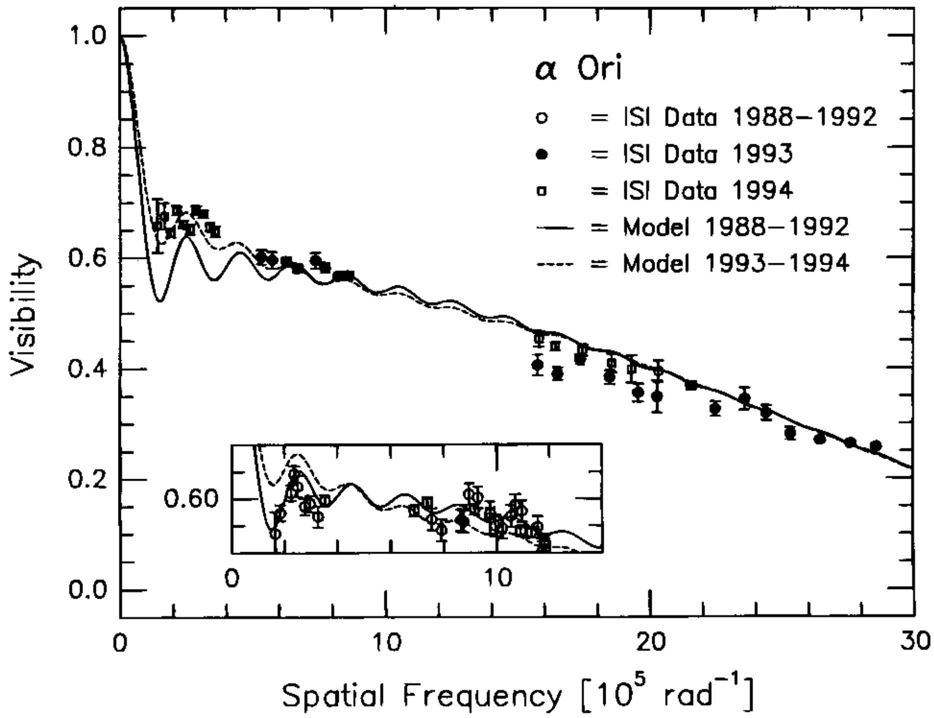

FIG. 2.—Visibility measurements of α Ori at 11.15 μm taken during 1993–1994, and models to fit these points. For spatial frequencies higher than about 10^6 rad^{-1}, the star is partially resolved. The solid curve assumes no dust closer to the star than 1″. The dashed curve assumes a new shell at a distance of 0″.1 and about 2% of the total mass of the outer shell. The inset shows the data of 1988–1992 for comparison with the solid curve based on no dust closer than 1″.

intensity to the total intensity, yielded essentially the same diameter and a precise estimate of the probable error. This calculation used a standard nonlinear least-squares fitting approach (Bevington 1969). It yields a diameter of 57.4 ± 0.3 mas, where 0.3 mas is the probable error.

Clearly there is good statistical precision to the fit, on the order of $\frac{1}{2}$%. However, the major source of error is not statistical; it is the relative calibration of the two data sets—the 10 m baseline data and the 32 m baseline data. The relative calibration is uncertain to approximately 7%, based on the measurements of α Tau. Thus, if the 1993 32 m baseline data, which appears slightly lower than the 1994 32 m baseline data, were recalibrated by 7%, the data at the two epochs would be more consistent with each other. In this case the best-fitting diameter is 55.7 ± 0.3 mas, somewhat smaller than before; χ^2 for the latter fit is significantly better than the previous one.

From the above fits, we take this set of data to give a stellar diameter of 56 ± 1 mas, assuming a uniform disk. Variations in temperature over the disk are relatively unimportant because the 11 μm radiation varies only approximately linearly with temperature. Limb darkening should also be relatively unimportant, since calculations predict a change in apparent diameter due to limb darkening of only about 1% at this wavelength, whereas at visible wavelengths it would be about 10%. Thus, from the apparent diameter of 52.7 ± 1.3 mas obtained from Tuthill (1994) at 700 nm, one would expect an apparent diameter of 57.4 ± 1.4 at 11 μm, which is in reasonable agreement with the value found here. This affirms theoretical estimates of limb darkening, though the precision of experimental determination of this effect is not high. For the best value of the actual stellar size, a small limb-darkening correction for 11 μm should be applied to the present results, giving a diameter of 56.6 ± 1.1 mas.

The effective temperature of α Ori is usually estimated at about 3500 K. To match the total luminosity (see White 1980), this is reduced to 3290 K if the diameter found here is used rather than the smaller diameters sometimes assumed at visible wavelengths. The effective radiation temperature for 11 μm and a diameter of 56 mas is approximately 2850 K. This temperature allows for an attenuation of the 11 μm radiation in interstellar space by a factor of 0.975, based on the estimate of White (1980) of the total luminosity attenuation by a factor of 0.860. Since the α Ori atmosphere is calculated to be rather more opaque at 11 μm than for visible or near-infrared radiation (see Alexander & Ferguson 1994), the shorter wavelengths may be emitted from somewhat more internal regions and be dominated by higher effective temperatures. No single temperature and diameter can fit all the radiative characteristics. Table 4 gives measured diameters for α Ori and α Sco, and Table 5 gives the calculated temperatures.

Observation dates and baselines used for the present results are listed in Table 1. These baselines were not changed very frequently because a number of different stars

TABLE 4

MEASURED DIAMETERS OF α ORI AND α SCO

Objects	D_{vis}[a] (mas)	$D_{11\,\mu\text{m}}$[b] (mas)	D[c] (mas)
α Ori......	52.7 ± 1.3	56.0 ± 1	56.6
α Sco......	40.0 ± 0.6	44.0 ± 2	44.4

[a] Diameter at visible wavelengths without limb-darkening corrections (see text).

[b] Diameter at 11 μm wavelength without limb-darkening correction (from present measurements).

[c] Actual diameter estimated from 11 μm value with a 1% correction for limb darkening.

TABLE 5

TEMPERATURES OF α ORI AND α SCO

Objects	T_{vis}[a] (K)	$T_{11\mu m}$[b] (K)	T[c] (K)
α Ori......	3290	3190	2850
α Sco......	3670	3500	2675

[a] Effective temperature from luminosity and assuming D_{vis}.
[b] Effective temperature from luminosity and assuming $D_{11\mu m}$.
[c] Effective temperature from 11 μm flux and $D_{11\mu m}$.

and types of observations were being made at each baseline; a change requires a few days of work and adjustment before measurement at a new baseline can be made. However, the changes in IR and visible flux with time, indicated by Figure 1 and Table 2, introduce no changes in the visibility values more than about 1%.

Freedom from some of the problems encountered at visible wavelengths appears to make stellar diameter measurements in the mid-infrared important enough so that in the future longer baselines will be arranged for the ISI and used so that values of visibility near zero for the larger stars can be obtained. This will require roughly doubling the baseline to about 70 m, and should markedly improve precision of diameter measurements, as well as provide a clearer determination of the extent to which stars such as α Ori change size.

3.1.3. *Recent Dust Emission*

It is clear from Figure 2 that the solid visibility curve—with its lower resolution points based on visibility results for α Ori about 3 years earlier (see Danchi et al. 1994) where no dust was detected near the star—does not fit the lower resolution measurements (spatial resolution $\lesssim 4 \times 10^5$ rad^{-1}) made in 1994. The sinusoidal variation of the visibility at low resolution is not now as marked as it was in the earlier data, and the visibility values are higher. This is evidence for the presence of a small amount of new dust close to the star; the data of 1994 are fitted by the dashed curve, derived from a model with a dust shell at a radius of 1″ as before, plus a new shell of dust at about 4 stellar radii or 0″.1 from the star. The total amount of new dust is small, being no more than about 2% of that in the dust shell near 1″ radius. However, being so close to the star, it produces enough 11 μm radiation to be noticeable. As it expands to a distance more like the radius of the previous shell, its 11 μm radiation will be too small to notice. This, of course, suggests that there may have occasionally been other such small emissions of dust, which are not now noticeable and were not previously detected.

There is additional confirming evidence of the new dust emission beginning in late 1994. The sharp increase in m_v by about 0.4, shown in Figure 1, with an accompanying slight increase rather than a decrease in the 11 μm flux is part of this evidence. If the amount of dust indicated by the visibility curve were uniformly distributed in a sphere around the star, the consequent increase in m_v due to absorption by dust would be only 0.08. Hence, if this decrease is not due to a temperature change but to dust alone, its distribution is not spherical but somewhat concentrated in our line of sight to the star. Another confirmation of the presence of new dust is the mid-infrared spectra shown in Figure 3. In Figure 3 it can be seen that the silicate emission peak at 9.7 μm, due to dust, increases steadily and significantly from 1994 August to 1995 March. It is not clear whether this gas and dust emission was due to unusual activity within α Ori or to the nearby presence of some external object, such as a companion for which there appears to be some evidence (Karovska, Nisenson, & Noyes 1986). However, it is clear that dust emission from α Ori is primarily due to episodic events and not to normal stellar atmospheric activity and radiation.

3.2. *α Sco*

3.2.1. *Visibility Curve and Diameter*

The visibility curve of α Sco at 11.15 μm measured during 1989–1990 has already been published for baselines of 4 and

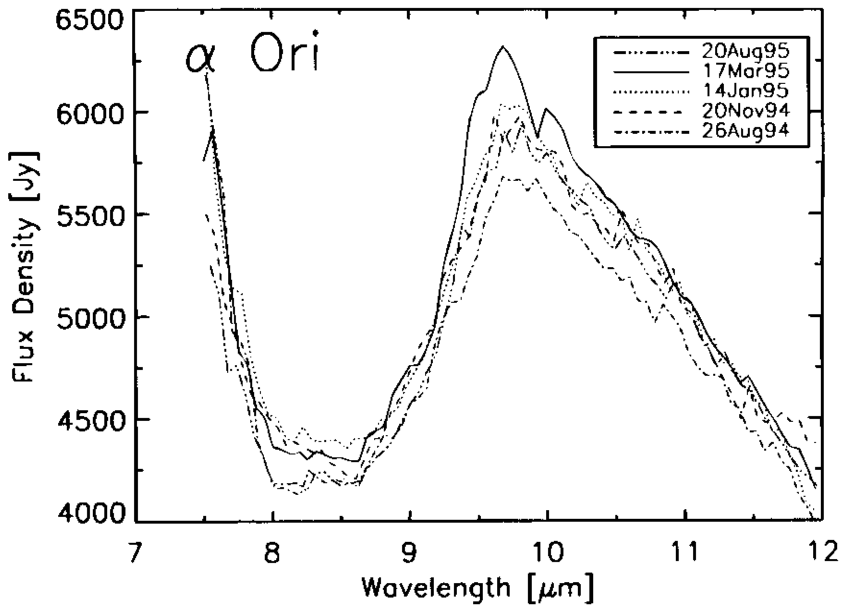

FIG. 3.—Spectrum of α Ori near 11.15 μm during the period 1994 August to 1995 August, showing a relative increase from 1994 August to 1995 March in the silicate peak near 9.7 μm, which indicates an increased dust component.

13 m (Danchi et al. 1994). The results of Sutton et al. (1977) taken in the late 1970s were also plotted there, and agreed well with the data of 1989–1990. These results showed that, as in the case of α Ori, the dust shell was many stellar radii from the star, and there was no significant amount of dust closer to the star than 1″. The baselines were not long enough, however, to resolve the stellar disk. Figure 4 shows new visibility data of α Sco with baselines as long as 32 m, which partially resolves the stellar disk. Since α Sco does not vary in luminosity as much as does α Ori and data from all periods seem to fit very well on the same curve, the previous data of 1989–1990 have been added to the more recent results of 1993–1994. Observation dates and baselines are given in Table 1. The best fit to the visibility curve gives a diameter of 44 mas. As was done with α Ori, the model-fitting procedure began with the previously published model (see Danchi et al. 1994, Fig. 20, Table 11). A uniform disk diameter was chosen, and the optical depth was varied until the minimum χ^2 for that diameter was found. A new diameter was chosen and the process repeated until an optimal global χ^2 was found. As with α Ori, an independent calculation with only a uniform disk was also made using a nonlinear least-squares fitting method. The fitted diameter obtained with this method agrees with the diameter derived above, and a precise estimate of the probable error was also obtained. The result is 43.6 ± 0.8 mas, where 0.8 mas is the probable error.

Measurements of α Sco at visible wavelengths are listed by White (1980). The average value of lunar occultation measurements listed there is 40.2 ± 1.8 mas, and the average of interferometry measurements, omitting two values which are very low ($\approx$28 mas), is 40.9 ± 1.8 mas. Richichi & Lisi (1990) also list other measurements and obtain a uniform disk model from their lunar occultation measurements of 38.9 mas with a formal error of only ± 0.1 mas. Tuthill (1994) gives a value of 37 mas after correction for apparent point sources, but notes that the value is not very reliable because of α Sco's lowness on the horizon, as seen from the location of the Herschel telescope. Values obtained over the past for the diameter of α Sco are not quite as variable as those of α Ori, perhaps because the star has not varied as much and has had fewer "hot spots," and perhaps also because its dust has been more distant from the star. An average of the three most reliable values above is 40.0 ± 0.6 mas. The 11 μm value of 44 ± 2 mas thus again indicates a limb darkening in the visible region very close to the expected 10%, though not with any great precision. Calculated temperatures for α Sco are listed in Table 5. These temperatures use the estimate of White (1980) of the total luminosity with an attenuation in the interstellar medium by a factor of 0.694, and hence also an attenuation of the 11 μm radiation by a factor of 0.941. As is the case for α Ori, the stellar diameter and 11 μm flux measured indicate a temperature for this radiation considerably smaller than that usually estimated from shorter wavelength radiation. The large difference in this case between temperatures calculated from total luminosity and from the 11 μm radiation is surprising. It may indicate a deviation from normal in the ratio of attenuation at the wavelengths involved, or, in fact, a large temperature drop in the stellar atmosphere.

4. CONCLUSIONS

Apparent diameters of α Ori and α Sco at visible wavelengths and at 11 μm are summarized in Table 4 along with the actual diameters as estimated from the apparent diameter at 11 μm wavelengths, with a 1% increase for limb darkening. The ratio of apparent diameters at visible wavelengths and 11 μm is very close to that expected from limb darkening, i.e., 0.91. The effective temperature at 11 μm is lower than that at shorter wavelengths by a few hundred degrees. Although many different diameters have been reported, it is not clear that α Ori changes size appreciably

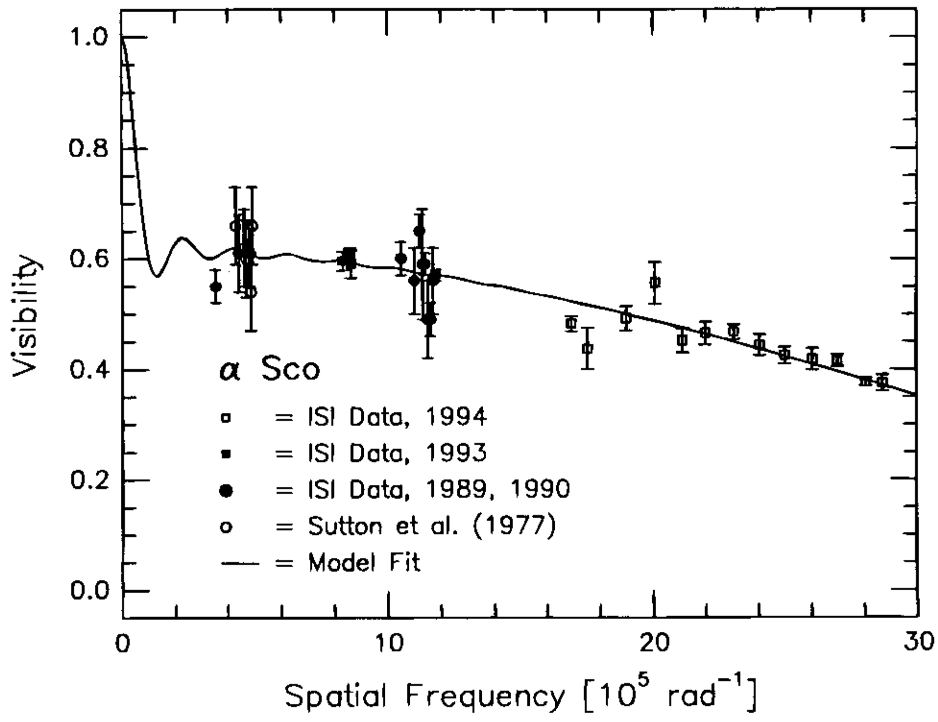

FIG. 4.—Visibility measurements of α Sco at 11.15 μm during the period 1977–1994 and a model fitting these points. At the higher spatial frequencies, the star is partially resolved.

with change in visible magnitude or with time. Present techniques should allow future determinations of any changes in size larger than 1% or 2%. Although α Ori has not emitted much dust for a number of years, a small burst of dust emitted in late 1994 has been detected.

We appreciate the help of K. Krisciunas in locating data on m_v for α Ori, and of K. D. Luedeke for providing his unpublished data. This work has depended on support from the Office of Naval Research (grant N00014-89-J-1583), from the National Science Foundation (grants AST-9016474, AST-9315485, and AST-9321289), and from the France-Berkeley Fund, for which we are grateful. One of the authors, D. M. was supported by the Programme National Haute Resolution Angulaire en Astrophysique and the Groupement de Recherche "Milieux Circumstellaires."

REFERENCES

Alexander, D. R., & Ferguson, J. W. 1994, ApJ, 437, 879
Bester, M., Danchi, W. C., Degiacomi, C. G., Townes, C. H., & Geballe, T. R. 1991, ApJ, 367, L27
Bester, M., Danchi, W. C., & Townes, C. H. 1990, in Amplitude and Intensity Spatial Interferometry, ed. J. B. Breckinridge, Proc. SPIE, Vol. 1237, 40–48
Bester, M., Degiacomi, C. G., Danchi, W. C., Greenhill, L. J., & Townes, C. H. 1992, in ASP Conf. Ser. 103, Robotic Telescopes in the 1990s, ed. A. V. Filippenko (San Francisco: ASP), 213–222
Bevington, P. R. 1969, Data Reduction and Error Analysis for the Physical Sciences (New York: McGraw-Hill), chap. 11
Bowen, G. H. 1988, ApJ, 329, 299
Bowers, P. F., Johnston, K. J., & de Vegt, P. 1989, ApJ, 330, 339
Buscher, D. F., Hariff, C. A., Baldwin, J. E., & Warner, P. J. 1990, MNRAS, 245, 7
Cheng, A. Y. S., Hege, E. K., Hubbard, E. N., Goldberg, L., Strittmatter, P. A., & Cocke, W. J. 1986, ApJ, 309, 737
Danchi, W. C. & Bester, M. 1995, Ap&SS, 224, 339
Danchi, W. C., Bester, M., Degiacomi, G. G., Greenhill, L. J., & Townes, C. H. 1994, AJ, 107, 1469
Diamond, P. J., Kemball, A. J., Junor, W., Zensus, A., Benson, J., & Dhawan, A. 1994, ApJ, 430, L61
Dyck, H. M., Benson, J. A., Ridgway, S. T., & Dixon, D. J. 1992, AJ, 104, 1982
Hearn, A. 1990, in From Miras to PN: Which Path for Stellar Evolution? (Gif-sur-Yvette: Editions Frontières), 121
Holzer, T. E., Fla, T., & Leer, E. 1983, ApJ, 275, 808
Karovska, M., Nisenson, P., & Noyes, R. 1986, ApJ, 308, 260
Krisciunas, K. 1990, Inf. Bull. Variable Stars, 3477
———. 1992, Inf. Bull. Variable Stars, 3728
———. 1994, Inf. Bull. Variable Stars, 4028
Lafon, J.-P., & Berruyer, N. 1991, A&A Rev., 292, 2
Lane, A. P., Johnston, K. J., Bowers, P. F., Spencer, J. H., & Diamond, P. J. 1987, ApJ, 323, 756
Luedeke, K. D. 1995, private communication (data available at AAVSO)
Michelson, A. A., & Pease, F. G. 1921, ApJ, 53, 249
Pijpers, F. P., & Habing, H. J. 1989, A&A, 215, 334
Quirrenbach, A., Mozurkewich, D., Armstrong, J. T., Buscher, D. F., & Hummel, C. A. 1993, ApJ, 406, 215
Richichi, A., & Lisi, F. 1990, A&A, 230, 355
Ridgway, S. T., Wells, D. C., & Joyce, R. R. 1977, AJ, 82, 414
Sanford, R. F. 1933, ApJ, 77, 110
Scholz, M., & Takeda, Y. 1987, A&A, 186, 200
Sutton, E. C., Storey, J. W. V., Betz, A. L., Townes, C. H., & Spears, D. L. 1977, ApJ, 271, L97
Tsuji, T. 1978, PASJ, 30, 435
Tuthill, P. G. 1994, Ph.D. thesis, Cambridge Univ.
White, N. M. 1980, ApJ, 242, 646
Wilson, R. W., Baldwin, J. E., Buscher, D. F., & Warner, P. J. 1992, MNRAS, 257, 369