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PRECISION MEASUREMENTS OF THE DIAMETERS OF α ORIONIS AND o CETI AT 11 MICRONS

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ABSTRACT

The angular diameters of α Orionis and o Ceti were measured at a wavelength of 11.15 μm using the two-telescope Infrared Spatial Interferometer (ISI). Based on fitting the visibility data to uniform disk models, the diameter of α Orionis is 54.7 ± 0.3 mas and that of o Ceti at phase 0.90 is 47.8 ± 0.5 mas. These diameters are the most precise ever measured in the mid-infrared, due in part to the addition of a 56 m baseline to the ISI, which provided sufficient resolution to observe the first zero in the visibility function of the stellar disks. Moreover, the effects of limb darkening and stellar hot spots are small at these wavelengths. Theoretically estimated limb-darkening effects indicate the actual diameters are approximately 1% ± 0.5% larger than the uniform disk approximation, or 55.2 ± 0.5 and 48.2 ± 0.6 mas for α Orionis and o Ceti, respectively.

Subject headings: infrared: stars — instrumentation: interferometers — stars: fundamental parameters — stars: individual (α Orionis, o Ceti)

1. INTRODUCTION

Mid-infrared interferometry provides a new opportunity for the precision measurement of stellar diameters. One reason for this is that blackbody emission in this wavelength regime is much less sensitive than shorter wavelengths to variations in source temperature, such as could be due to stellar hot or cool spots. Hence, in the mid-IR, a more uniform intensity over the stellar surface can be expected. Furthermore, the effect of limb darkening is much less than that at shorter wavelengths. Material surrounding a star tends to obscure or darken the outer parts of a star more than it does the center and, hence, decrease its apparent size if it is assumed to be a disk of uniform intensity. These gases are generally much more transparent in the mid-IR region than at visible wavelengths, and hence the resulting apparent diameter is closer to the actual photospheric diameter. Often, the precision and extent of visibility measurements do not allow adequate experimental determination of the amount of limb darkening, and the resulting fits are made to a uniform disk model. Jacob et al. (2000) emphasize the uncertainties in measurement of size of M giants and Mira due to limb darkening, but their theoretical models do not extend to wavelengths longer than 1.1 μm. Estimates based on simple models predict limb-darkened stellar diameters to be smaller than actual diameters by about 1% in the mid-IR, as compared to 10% in the visible (cf. Bester et al. 1996; Manduca 1979; Scholz & Takeda 1987). In addition, longer wavelengths will scatter less from any circumstellar dust which may be present. This type of scattering can cause an apparent increase in the diameter of a star having a significant dust shell (Tsuji 1978).

Previously, the diameter of α Orionis has generally been measured using interferometry at visible wavelengths. The results have spanned the range of approximately 42–52 mas before corrections for limb darkening (see Cheng et al. 1986; Buscher et al. 1990; Wilson et al. 1992). Our measurement of 54.7 mas based on a uniform disk model is larger than these, probably mostly due to the lessening of limb darkening in the infrared. Near-infrared measurements have been made by Dyck et al. (1992), and a diameter of 44.2 ± 0.2 mas was reported (before correcting for limb darkening, which was estimated to increase the size to 46.1 ± 0.2 mas). The Infrared Spatial Interferometer (ISI) has previously measured the diameter of α Orionis at 11 μm (using shorter baselines than those currently available) to be 56.0 ± 1 mas (Bester et al. 1996). This is consistent with, but not as accurate as, the present measurements using a 56 m baseline.

Limb-darkening effects are discussed in more detail below and believed to be no more than about 1%. Although in principle there could be limb brightening which would enlarge the apparent size, no present models predict limb brightening, so the large size found here at mid-IR wavelengths should represent a more correct diameter than the smaller ones found at shorter wavelengths.

The diameter of o Ceti has also been measured at optical and near-IR wavelengths. Measurements at 700 nm by Tuthill, Haniff, & Baldwin (1995) were fit with a Gaussian brightness profile whose FWHM varied between 27 and 38 mas depending on its phase. Ridgway (1992) reported the apparent diameter of o Ceti at 2.2 μm to be 36.1 ± 1.7 mas (without limb-darkening corrections). Previous ISI measurements of o Ceti have only partially resolved its dust shell but were used to estimate its photospheric diameter at 11 μm to be between 38 and 48 mas (Lopez et al. 1997), consistent with the present measurement of 47.8 ± 0.5 mas.

2. OBSERVATIONS AND ANALYSIS

Visibility measurements were made using the Infrared Spatial Interferometer (ISI) located at Mount Wilson, California. It consists of two movable telescopes that use heterodyne detection to measure fringe visibilities at spatial frequencies between 2×10^5 and 50×10^5 rad^{-1}. These data were taken while operating at a wavelength of 11.15 μm and a maximum baseline of 56 m. A thorough description of the instrument and its performance can be found in

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Hale et al. (2000). Measurements of α Orionis were made on 1999 November 11 and 12, and those of *o* Ceti on 1999 October 22, 26, and 27, and November 10, 11, and 19, at an average phase of 0.90. The orientation of the measured stellar diameter was approximately 65° east of north for α Orionis and 70° east of north for *o* Ceti.

The diameters of α Orionis and *o* Ceti were calculated by fitting the visibility data with a curve modeling the visibility of a uniform stellar disk. For such a brightness distribution, the visibility as a function of spatial frequency in one dimension, $V(x)$, is given by

$$V(x) = \frac{2AJ_1(2\pi rx)}{(2\pi rx)} , \quad (1)$$

where x is the spatial frequency in rad^{-1}, J_1 is the Bessel function of order unity, r is the radius of the stellar disk in radians, and A is an overall amplitude factor, which is unity for a uniform disk but is less than one if a surrounding dust shell is present. The ISI measures the square of the visibility, which is the ratio of fringe power to the product of the total power measured in each telescope. These values were calibrated by observing either an unresolved star or a star with a well-known diameter having no substantial dust, such as α Tau or α Boo. It should, however, be noted that any error in the calibration will be absorbed into the constant A when fit and should not affect the diameter measurement. Furthermore, the constant A has no significant role in stellar size measurement, since its value depends on the ratio of stellar luminosity to that of the combined star and surrounding dust. The shape of the visibility curve, and hence relative values rather than any scale factor, determines the stellar size.

The visibility is measured over a range of spatial frequencies using the technique of Earth rotation synthesis. A best fit of the two free parameters in equation (1) was obtained by minimizing χ^2 with respect to A and r:

$$\chi^2 = \frac{\Sigma[V^2(x_i) - V_i^2]^2}{\sigma_i^2} , \quad (2)$$

where the data $(x_i,\ V_i^2)$ have a statistical width σ_i calculated from repeated measurements in a single spatial frequency bin. The square of the visibility was fit as opposed to its absolute value because that was the directly measured quantity, and an optimum theoretical fit is more straightforward. The fluctuations in measurement are approximately uniform for V^2 and hence not uniform for V. Furthermore, near zero-visibility fluctuations cause some small negative values of the visibility squared, or imaginary values for the visibility. The error in the best-fit stellar radius parameter was estimated by searching for the two radii, $r + dr^+$ and $r - dr^-$, which would increase the normalized χ^2 by unity, while maintaining minimization with respect to A. The average of the dr was taken to be the error in the stellar radius. This general procedure is outlined in Bevington (1969). The use of the normalized χ^2 causes the fit of the stellar radius to have an error which depends only on the spread of the data about the best fit and not on the magnitude of the σ_i.

The long-baseline visibility data for α Orionis is plotted in Figure 1, which includes baselines long enough to include zero visibilities. This plot shows the individual data, $(x_i,\ V_i^2)$, binned into groups of five so as to be clearer to the eye, with error bars given by the standard deviation of the mean. The best-fit uniform disk model, which occurs at a radius of 27.37 mas, is also plotted. For this fit, $\chi^2/(N-2) \approx 0.3$, indicating that a uniform disk model fits the data as well as can be expected from these measurements. The probable error in the radius, dr, was determined to be 0.17 mas.

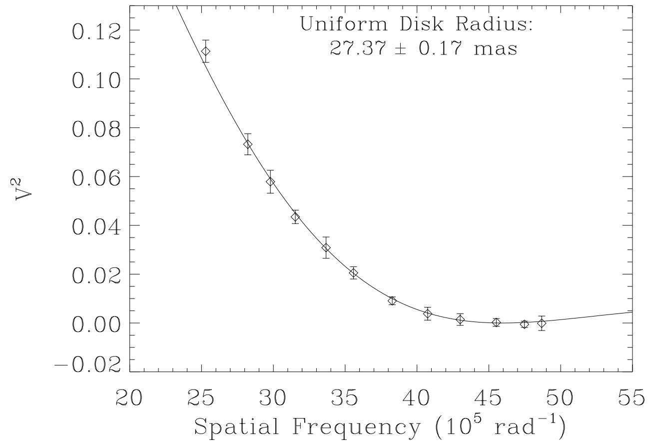

FIG. 1.—Long-baseline visibility data from 1999 for α Orionis (*individual points*) and uniform disk model fit (*solid curve*). The theoretical curve gives a visibility of zero at a spatial frequency of 46.0 × 10^5 rad^{-1}.

The *o* Ceti visibility data are plotted in Figure 2. This plot shows the individual data, V_i^2, binned so as to be clearer to the eye, with error bars given as before. The best-fit uniform disk model, for which the radius parameter $r = 23.91$ mas, is also shown. This fit has a ratio $\chi^2/(N-2) \approx 0.25$, illustrating the quality of the fit. The probable error in the radius, dr, was determined to be 0.24 mas. The phase of *o* Ceti was approximately 0.90 at the time of measurement. Thus, the star was near maximum luminosity at measurement, and its diameter may have been affected by this.

3. LIMB-DARKENING EFFECTS

The effects on apparent stellar size due to limb darkening provide some uncertainty in the real size of the photosphere. Theoretical estimates generally conclude that these

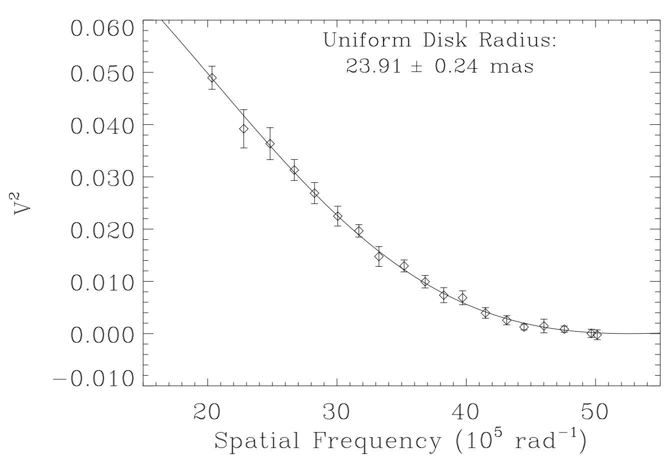

FIG. 2.—Long-baseline visibility data from 1999 for *o* Ceti (*individual points*) and uniform disk model fit (*solid curve*). The theoretical curve gives a visibility of zero at a spatial frequency of 52.7 × 10^5 rad^{-1}.

effects decrease approximately, but somewhat more slowly than, inversely proportional to the wavelength. The effect of limb darkening on apparent size is estimated to be about 10 times less at 10 μm than in the visible region (cf. Manduca 1979; Scholz & Takeda 1987). However, for stars with molecular gas around them, limb-darkening effects do not decrease uniformly with increasing wavelength but depend on the spectra of the molecules involved, so that limb darkening may be substantially different from standard estimates if strong spectral lines not included in the estimates are present.

Measurements of the diameter of α Orionis were made on 2000 January 25 at 2.25 μm, and the effect of surrounding gases is evidently present. The diameter of α Orionis was measured in a narrowband filter, using nonredundant aperture masking on the Keck I telescope (Tuthill et al. 2000). The central wavelength was 2.249 μm, and the FWHM of the filter was 0.024 μm. The calibrator star for this procedure was α Tau, and a diameter of 19.75 mas was assumed based on the K-band measurements of Perrin et al. (1998). Figure 3 plots the azimuthally averaged visibility data as well as the best-fit uniform disk model. Assuming a uniform disk, the resulting diameter was 42.6 ± 1.9 mas, where the dominant uncertainty arises from calibration of the seeing conditions as opposed to statistical errors in the measured values. In order not to bias our estimate of the diameter, the visibility at the origin was left as a free parameter during fitting to accommodate small miscalibration. The measured diameter is much smaller than most measurements at visible wavelengths but in reasonable agreement with the value 44.2 ± 0.2 mas found at near-IR wavelengths by Dyck et al. for the uniform disk model. This indicates substantial darkening due to absorption in the 2.25 μm region by material immediately surrounding the star and illustrates the problem of obtaining reliable measurements of stellar size. In the mid-IR region, the only known important absorption lines due to material close to α Orionis are those of H_2O (Jennings & Sada 1998).

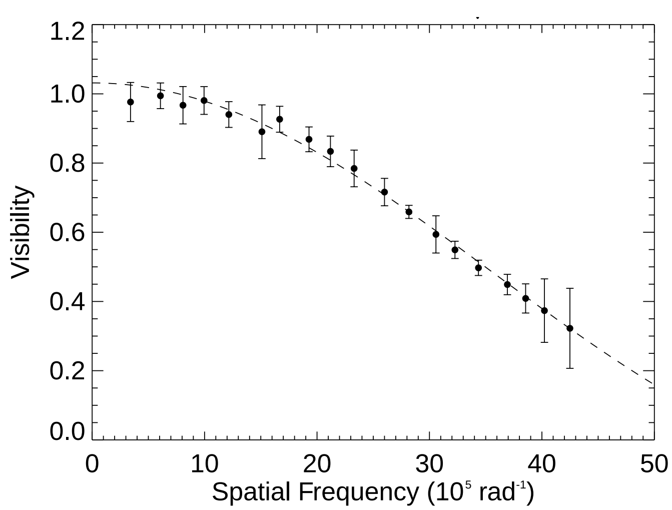

FIG. 3.—Keck Telescope aperture masking visibility data for α Orionis at 2.25 μm (*individual points*) and 42.6 ± 1.9 mas diameter uniform disk model fit (*dashed curve*).

The ISI measures size in the mid-IR region using heterodyne detection of radiation over the narrow bandwidth of 6 GHz, or 0.2 cm^{-1}. Measurements reported here were centered at a wavelength of 11.15 μm. Some water lines occur in this frequency range which, according to theoretical predictions from the HITRAN program (cf. Rothman et al. 1998), are substantially weaker than those measured in α Orionis near 12.3 μm (Jennings & Sada 1998). Using this information, and assuming the water vapor is adjacent to the photosphere, we estimate that the resulting limb darkening due to water would decrease the apparent size of α Orionis by about 0.3%, or 0.16 mas. If the water vapor is farther from the star, its effect on apparent diameter would be somewhat less.

Mid-IR spectra of o Ceti are not as well known as those of α Orionis. Hence, no good estimate of limb darkening of o Ceti can presently be made, and the diameter obtained for o Ceti is not as certain as that of α Orionis. However, it is notable that the diameter of o Ceti found at 11.15 μm wavelength is roughly 25% larger than what has been reported from visible measurements. Presumably, this is due to the lessening of limb-darkening effects, but perhaps also it could have been affected by the phase being near maximum luminosity.

The ISI's use of heterodyne detection provides very narrow frequency bandwidths, with a central frequency which can be selected from a number of lines of isotopes of CO_2, since a CO_2 laser is the local oscillator. The particular frequency chosen for present measurements is relatively free of strong H_2O lines. However, in the future, a variety of narrow bandwidth regions in the mid-IR can be used to remeasure the size of α Orionis and o Ceti and thus detect and allow avoidance of any limb-darkening effects on the apparent size due to spectral lines.

4. CONCLUSIONS

Theoretical models indicate that the interferometric data discussed here can be characterized by a uniform disk quite well. This allows an accurate determination of the apparent size of α Orionis and o Ceti for such a model. The best-fit diameters are 54.7 ± 0.3 and 47.8 ± 0.5 mas, respectively. These precise measurements of their sizes become physically accurate when coupled with knowledge that the mid-IR exhibits only small limb-darkening effects and much less sensitivity to source temperature irregularities than measurements at shorter wavelengths. Allowing for the expected but somewhat uncertain amount of limb darkening at 11 μm wavelength, the actual photospheric diameter of each star in question is estimated to be 1.0% ± 0.5% larger than that obtained from a uniform disk model, or 55.2 ± 0.5 and 48.2 ± 0.6 mas, for α Ori and o Ceti, respectively.

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