The Variability of Late-Type Stars' Diameters Measured Using Mid-Infrared Interferometry

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ABSTRACT

The size and variability of the photospheres of several late-type stars has been probed using 11 micron heterodyne interferometry. High resolution observations performed during the years 1999-2001 yielded diameter measurements accurate to about 1% for α Ori and o Cet, a supergiant and a mira variable. Narrow bandwidths (0.17 cm^{-1}) and high resolution spectra were used to avoid molecular lines. Observations were made at several different wavelengths, sometimes purposely overlapping an observed spectral feature. In all cases, the 11 micron sizes are larger than previously measured visible and near-infrared diameters. The discrepancies will be discussed. In addition, a variation of the diameter of Mira with phase has been observed.

Keywords: Stellar diameters, infrared interferometry, Mira, o Cet, α Ori

1. INTRODUCTION

There is little ambiguity in referring to the diameter of a main-sequence star like the sun. The sun is observed to be a bright circular disk with a well-defined edge not very dependent on wavelength. Late-type AGB stars, including the supergiants and Mira variables discussed below, are very different objects. Although direct images of their stellar surfaces are inaccessable, available evidence suggests that these stars have no unique diameter. Their apparent size and shape are extraordinarily dependent on wavelength and change with time.

In general, AGB stars have radii several hundred times that of the sun, with comparable masses in some cases. As a consequence, their surface gravities are many orders of magnitude lower, causing extension to their atmospheres. Very often, material escapes from the gravitational field of the parent star and mass-loss occurs. Particle densities great enough to be opaque at some wavelengths are present at radii several times what might be considered their surface.

AGB stars also are characterized by their cool temperatures. Miras can have surface temperatures as low as perhaps 2500 K. These stars radiate in the infrared predominantly. Their visible intensities are extremely dependent on temperature. At 2500 K, a 1% increase in temperature will increase the intensity of a blackbody by 10% at 600 nm as opposed to only 1.3% at 11 μm. As a result, small variations in temperature within the star are exaggerated in the visible and a non-uniform intensity distribution is produced which becomes more uniform at longer wavelengths.

Low temperatures in the atmospheres of AGB stars affect the state of the gases and complicated matter-radiation interactions can occur. Particularly, molecules including H_2, CO, and several oxides form at temperatures lower than about 3000 K. These molecules have forests of spectral lines which introduce opacity at large radii at some wavelengths and are capable of redistributing the spectral energy distribution significantly. Dust also forms in circumstellar regions where the temperature is cooler than about 1300 K (Lobel *et al.*, 1999[1]). Mid-IR wavelengths and a narrow bandpass appear to be optimum for penetrating the dust and gas and obtaining a representative stellar diameter.

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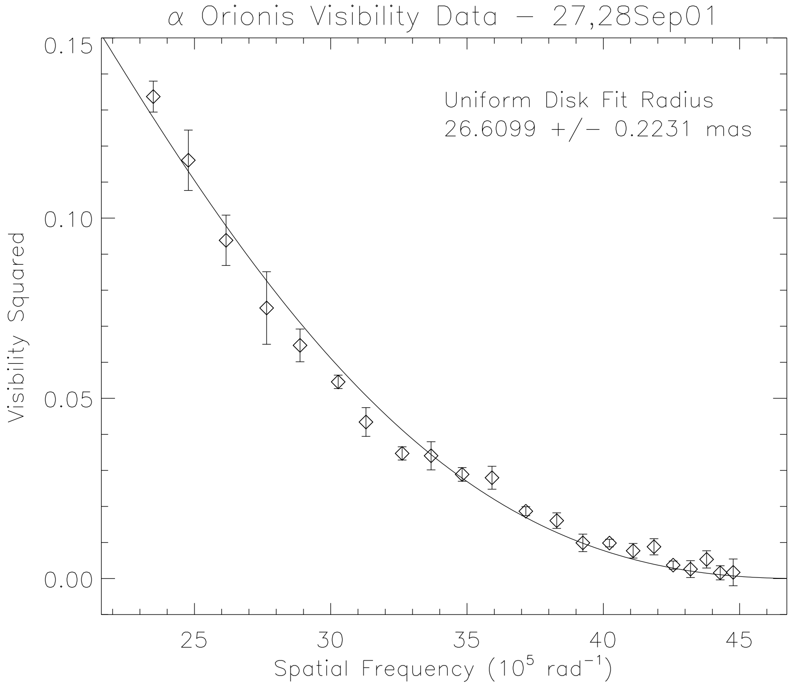

Figure 1. α Ori Visibilities (diamonds) and Best Fitting Uniform Disk Curve (solid line) from 27,28Sep01

2. ISI MID-INFRARED DIAMETERS COMPARED WITH OTHER MEASUREMENTS

The Infrared Spatial Interferometer (ISI) is a heterodyne detection interferometer using a CO_2 laser local oscillator usually operating at 11.15 μm. A complete description can be found in Hale *et al.* (2000).[2] Baselines up to 56 m were used to measure visibilities of α Ori and o Cet. The diameter is obtained from the data by finding the best fitting disk of uniform intensity having radius which minimizes χ^2. At 11 μm, a significant fraction of the source radiation comes from a large extended dust shell which is almost completely resolved at the spatial frequencies considered. The effect of the dust is to lower the extrapolated visibility at relatively low spatial frequencies by an amount equal to the fraction of light emanating from the extended dust shell. So, we allow in the fitting, a second free parameter which is the fraction of light coming from the stellar disk itself. It should be noted that any error in calibration will be absorbed into this coefficient and will not affect the measured diameter. The error in the best fit radius was estimated by finding nearby radii which increase the normalized χ^2 by unity (Bevington, 1969).[3] α Ori visibilities from the nights 27,28Sep01 and the best fitting uniform disk is shown in Figure 1.

The wide variety of techniques and instruments capable of high resolution studies have led to an impressive quantity of stellar size measurements. Tables 1 and 2 are a compilation of some of the more recent diameters for α Ori and o Cet, including the ISI diameter of α Ori from above and three ISI measurements of o Cet. Listed is the wavelength of observation, the phase (for o Cet), the apparent diameter measured, the technique used to achieve the high angular resolution, and the telescope utilized. Generally, Table 1 shows α Ori visible diameters which vary by roughly 30% depending on wavelength, more constant near-infrared diameters near the lower bound of the visible sizes, and mid-infrared ISI diameters about 25% larger than these. The o Cet diameters in Table 2 follow the same pattern but have larger discrepancies. Visible and near-IR o Cet sizes vary by more than a factor of 2. The ISI mid-infrared continuum sizes are roughly twice the smallest near-IR sizes. Additionally, some of the sizes measured at similar wavelength, but different phases, show changes with phase.

The variations in apparent size of α Ori and o Cet can be understood by considering the many effects which could bias the diameter measurements. The presence of molecular gas in the stellar atmosphere introduces

Table 1. α Ori Diameter Measurements Using Various Techniques and Instruments

λ (μm)	Diam. (mas)	Method*	Instrument$^{\text{ref}}$
0.370	52 ± 6	AM	KPNO 4m Telescope[4]
0.410	51 ± 2	AM	KPNO 4m Telescope[4]
0.520	50 ± 1	AM	KPNO 4m Telescope[4]
0.546	57 ± 2	AM	Herschel Telescope[5]
0.550	48 ± 1	AM	KPNO 4m Telescope[4]
0.633	55 ± 1	AM	Herschel Telescope[5]
0.650	58 ± 1	AM	KPNO 4m Telescope[4]
0.656	44 ± 1	AM	KPNO 4m Telescope[4]
0.700	49 ± 3	AM	Herschel Telescope[5]
0.710	54 ± 2	AM	Herschel Telescope[5]
0.830	51.1 ± 1.5	I	COAST[6]
0.850	46 ± 1	AM	KPNO 4m Telescope[4]
0.854	43 ± 1	AM	KPNO 4m Telescope[4]
1.09	42	AM	Keck Telescope[7]
1.28	42	AM	Keck Telescope[7]
1.64	41.5	AM	Keck Telescope[7]
2.12	42	AM	Keck Telescope[7]
2.2	44.2 ± 0.2	I	Michelson Array[8]
3.09	48	AM	Keck Telescope[7]
3.75	40.2 ± 0.2	I	IOTA[9]
11.15	**53.2 ± 0.4**	**I**	**ISI, continuum**
several	41.0 ± 0.8	P	several[10]

*AM: aperture masking, I: interferometry, P: infrared photomotry

opacity due to spectral lines. If the line is optically thick and hot gas exists at large radii, the star will appear larger at that line. If the gas is close to the photosphere and cool relative to it, limb darkening will dominate and a smaller apparent size will be measured. The most important spectral lines in O-rich AGB stars are due to H_2O and TiO. The transitions due to these molecules are illustrated in Figures 2 and 3. Most of the diameter measurements in Tables 1 and 2 utilize wide bandpasses and the inclusion of some of these spectral lines is unavoidable. Many of the variations in visible and near-IR sizes are attributable to spectral lines. The ISI uses an assortment of narrow (0.17 cm^{-1}) bandpasses and through the use of measured high resolution spectra can select line-free continuum observing regions in which to measure diameters. (Mid-IR spectra and ISI bandpasses are described in Section 4.) In O-rich AGB stars, silicate dust which forms at several stellar radii also can absorb and scatter light, further obscuring the true stellar surface. Figure 4 shows the opacity due to silicate dust as a function of wavelength. The effect of dust on 11 μm sizes is discussed in Weiner (2002)[19] and is shown to be negligible in α Ori and less than ±3% in o Cet.

Asymmetric surface non-uniformities, including stellar hotspots have been predicted and observed in α Ori and o Cet and are capable of lowering apparent sizes. Wilson *et al.* (1997)[20] claimed that at least three bright spots were observed on α Ori at 700 nm totaling more than 20% of the flux and changing in position on a weekly time-scale. Asymmetry in o Cet has been observed by Karovska *et al.* (1997),[21] Wilson *et al.* (1992),[5] and Josselin *et al.* (2000).[22] Schwarzschild (1975)[23] argues that convective granules, observed on the solar surface to have typical size $0.003R_{\odot}$, should exist on the surface of supergiants having a width on the order of the stellar radii. Variations in surface temperature due to these granules are predicted to be as high as 1000 K. Due to the extreme temperature dependence of intensity at shorter wavelengths for low effective temperatures, such a hotspot may be the dominant feature of the star in the visible. Stellar hotspots are likely to lower visible and near-IR apparent sizes relative to 11 μm sizes, however for such large disparities as are observed in Table 2, hotspots would need to be even more extreme than are predicted by Schwarzschild. The cause of

Table 2. *o* Cet Diameter Measurements Using Various Techniques and Instruments

λ (μm)	Phase	Diam. (mas)	Method*	Instrument$^{\rm ref}$
0.700	0.05-0.58	41 - 44	AM	Herschel Telescope[11]
0.710	0.05-0.58	46 - 53	AM	Herschel Telescope[11]
0.800	0.96	33	I	Mark III[12]
0.800	0.05	26	I	Mark III[12]
0.800	0.14	26	I	Mark III[12]
0.833	0.05	42.3 ± 3.4	AM	Herschel Telescope[11]
0.902	0.05-0.58	36 - 38	AM	Herschel Telescope[11]
0.905	0.67	42.0 ± 1.0**	I	COAST[13]
1.024	0.67	36.3 ± 1.0**	I	COAST[13]
1.09	0.95	25	AM	Keck Telescope[7]
1.290	0.67	31.3 ± 0.5**	I	COAST[13]
1.28	0.95	20	AM	Keck Telescope[7]
1.64	0.95	28.5	AM	Keck Telescope[7]
2.12	0.95	34	AM	Keck Telescope[7]
2.2	0.94	28.8 ± 0.1	I	IOTA[9]
2.2	0.23-0.36	36.1 ± 1.4	I	Michelson Array[14]
3.09	0.95	60	AM	Keck Telescope[7]
3.75	0.98	43.5 ± 0.2	I	IOTA[9]
11.09	**0.20**	**63.7 ± 1.1**	**I**	**ISI, spectral line**
11.15	**0.20**	**54.2 ± 0.6**	**I**	**ISI, continuum**
11.15	**0.36**	**49.9 ± 0.7**	**I**	**ISI, continuum**
several	0.5-1.1	24 - 39	P	several[15]

*AM: aperture masking, I: interferometry, P: infrared photometry
**Implied uniform disk diameter. The reference listed a Gaussian FWHM which is a factor of ≈ 1.61 times smaller.

such a non-uniformity may be linked to non-radial pulsation, or other dynamic phenomenon, rather than being convective in nature.

3. VARIATION OF DIAMETER WITH PHASE IN *o* Cet

A variation in the diameter of *o* Cet with phase has been observed with the ISI at 11 μm. The diameter was measured between 23Oct01 and 02Nov01 at a variability phase of 0.20 to be 54.2 ± 0.6 mas. On 19Dec01 at phase 0.36, using the same bandpass, a diameter of 49.9 ± 0.7 mas was observed. The 11.149 μm bandpass which was used is known to not contain any significant spectral lines (see Section 4), and the change in diameter is believed to reflect pulsation of the continuum photosphere of *o* Cet. The visibility data and best fitting uniform disk for each phase is shown in Figure 5. Assuming the size variability is sinusoidal and maximum at phase 0.15 (see Weiner (2002)[19]) the observed change implies a change in diameter over the entire cycle by ± 12.7%. By comparison, the dynamical fundamental mode model of Bowen (1990)[24] predicts the photospheric shells to change in radius by ± 11.8%.

The fraction of flux coming from the star was also seen to decrease from 32.5% at phase 0.20 to 27.7% at phase 0.36. N-band photometry from earlier years at similar phases reveals a decrease in mid-infrared flux by about 25% over this interval (Lopez *et al.* (1997)[25]) implying a decrease in *stellar* flux of 31.6%. Assuming the observed change in diameter, this is equivalent to a decrease in stellar intensity by 19.2% and consistent with, for instance, a decrease in stellar temperature from 2700 K to 2350 K.

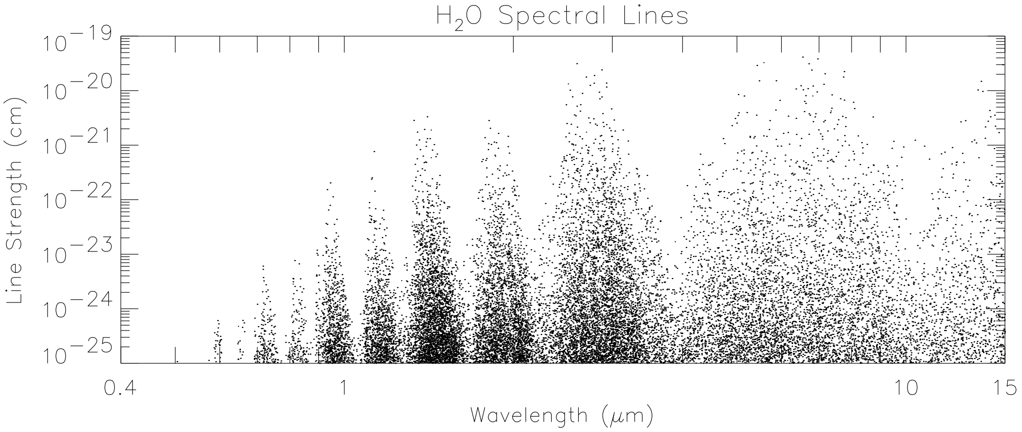

Figure 2. Strength of H_2O Transitions at 1250 K (from Rothman *et al.* (1992)[16])

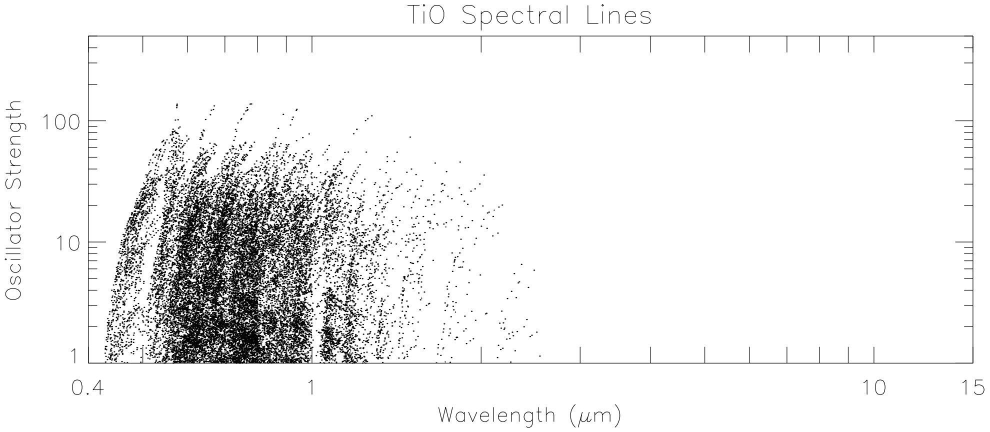

Figure 3. log gf Values for TiO Transitions (from Jorgensen (1994)[17])

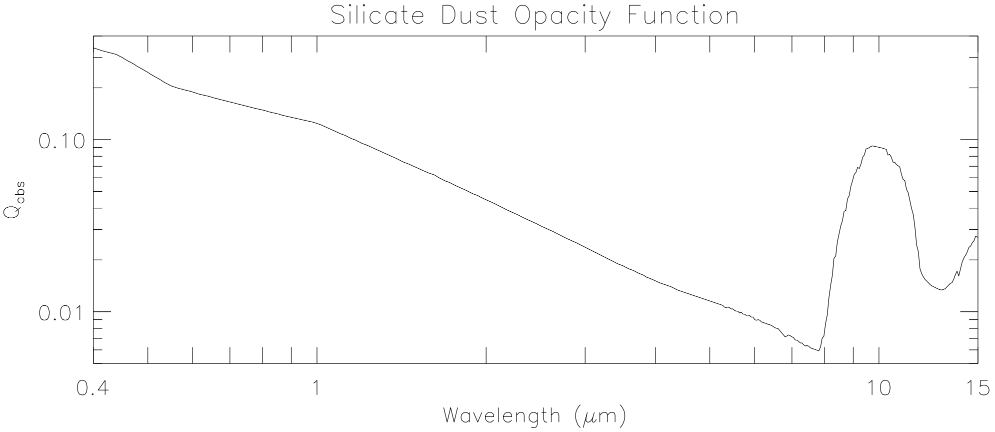

Figure 4. Opacity of "Warm" Silicate Dust (from Suh (1999)[18])

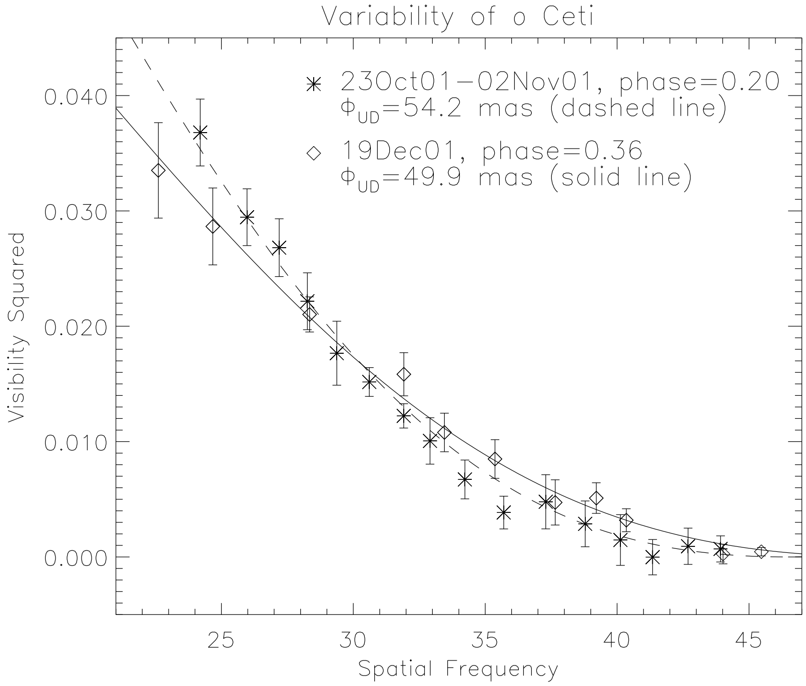

Figure 5. *o* CetVisibilities and Best-Fitting Uniform Disk at Two Different Phases

4. INCREASED DIAMETERS MEASURED ON H_2O LINES

High resolution 11 μm spectra of *o* Cet and α Ori were recorded at the IRTF telescope with the TEXES instrument.[*] Strong emission lines identified as H_2O were seen in *o* Cet having an excitation temperature around 1100 K and a column density of $\sim 10^{19}$ cm^{-2}. A characteristic absorption line was observed at wavenumber 0.033 cm^{-1} lower than each emission peak in *o* Cet. Some H_2O absorption lines were observed in α Ori with a temperature of $\sim$1750 K and a much lower column density (Weiner, 2002[19]). The spectra of α Ori surrounding the 11.149 μm bandpass and the spectra of *o* Cet around both the 11.149 μm and 11.086 μm bandpasses are shown in Figure 6. The vertical dashed lines show the edges of the bandpass as they would appear at the dates when visibility data were taken.[†] H_2O lines from HITRAN/HITEMP (Rothman, 1994[16]) at a temperature of 1750 K for α Ori and 1000 K for *o* Cet are plotted as vertical bars below the spectra with the scale given on the right axis. The 11.149 μm bandpass does not appear to contain any spectral lines stronger than about 5% and the strongest H_2O line within the bandpass has strength $\sim 5 \times 10^{-24}$ cm. Assuming reasonable parameters for the gas temperature and location (see Weiner, 2002[19]) the effect of H_2O on the 11.149 μm diameter measurements will be less than 0.1%. If some other gas is present and responsible for the $\sim$5% absorption feature seen within the 11.149 μm bandpass in *o* Cet, an upper limit of $\sim$1% can be placed on the effect it may have on the continuum diameter measurements at 11.149 μm (see Weiner, 2002[19]). The 11.086 μm bandpass, however, contains an obvious H_2O spectral feature due to a transition with strength 3.4×10^{-21} cm.

The diameter measured at 11.086 μm on 25,26Oct01 and 02Nov01 was significantly larger than the continuum 11.149 μm size measured on 23,24Oct01 and 02Nov01. Visibilities from each of the bandpasses and the best fitting uniform disk are plotted in Figure 7. A clear increase in size due to the spectral line in apparent. The 17.5% increase in apparent size of *o* Cet with a spectral line present contains some information on the radii where H_2O exists. If one assumes that the gas responsible for the emission line is optically thick, and that

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[*] The observations were carried out by John Lacy and Matt Richter, and a description of the instrument can be found in Lacy *et al.* (2002).[26]

[†] The doppler shift due to earth's orbit will cause the spectra to shift in frequency and the bandpass will appear to change position over the course of the year.

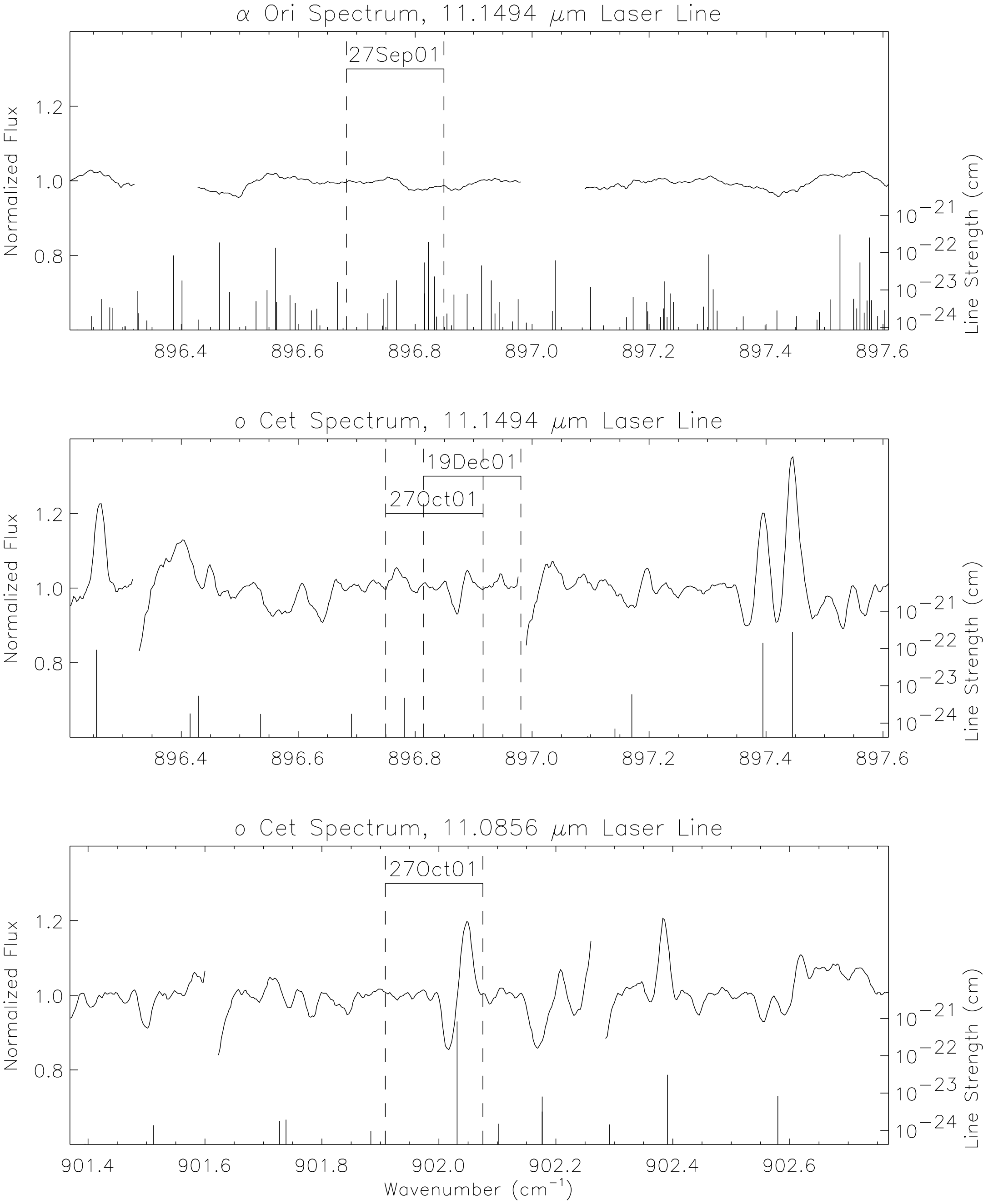

Figure 6. Spectra of α Ori and o Cet Surrounding ISI Bandpasses. The vertical dashed lines mark the edges of the bandpass as it would appear on the dates which visibility data were taken. H_2O line strengths[16] at a temperature of 1750 K and redshift of 39 km/s for α Ori and 1000 K and 83 km/s for o Cet are plotted as vertical bars with the scale given on the right axis.

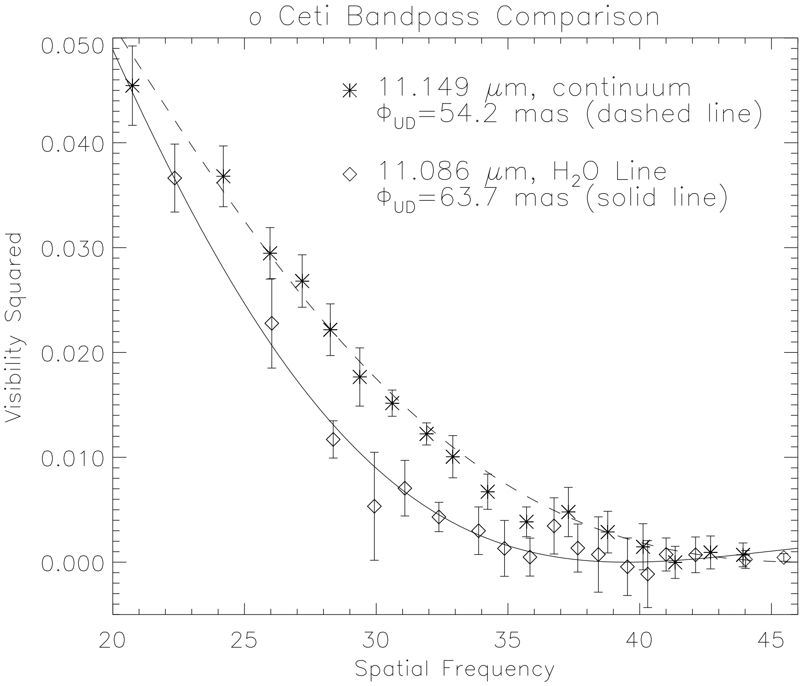

Figure 7. *o* Cet Visibilities and Best Fitting Uniform Disks from the 11.149 μm Continuum Bandpass and the 11.086 μm Bandpass which Contains a Strong H_2O Line. The two observations were performed within a few days of each other.

the absorption line doesn't affect the apparent size very much, we can estimate that the size change is due to a large apparent size at the wavelength of the emission line, averaged with the continuum size in the rest of the bandpass. For simplicity, let us assume that the intensity profile at the wavelength of the emission line is uniform disk-like, the temperature of the gas is 1500 K and the star is 2500 K, and that the emission line fills one-fourth of the bandpass. In this case, the radius of the opaque gas shell would need to be $1.78R_*$ in order to increase the apparent size of the star by 17.5%. This implies that H_2O densities on the order of 10^{11} m^{-3} are required at roughly 1.7 stellar radii to cause the H_2O to be opaque.

ACKNOWLEDGMENTS

This work was supported in part by the National Science Foundation (AST 97-31625) and the Office of Naval Research (N00014-89-J-1583).

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