VARIATIONS IN THE SPATIAL DISTRIBUTION OF 11 MICRON RADIATION FROM OMICRON CETI*

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ABSTRACT

The spatial distribution of 11 micron radiation from o Ceti has been observed at various phases of its light cycle using a stellar interferometer. Changes have been seen which can be attributed to variation in the strength of thermal emission from circumstellar dust relative to the stellar continuum at 11 microns. These changes are shown to be correlated with the changes in luminosity of o Ceti in such a way that dust grain emission at 11 microns was increased more than the continuum during the period of maximum luminosity. The degree of the change in dust grain emission implies that the maximum dust temperature is in the range of 500 K to 700 K during minimum stellar luminosity.

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I INTRODUCTION

Long-period variable stars commonly are surrounded by circumstellar dust shells. Variations in the luminosities of these stars will greatly change the radiative environment of the dust grains; thus it is expected that variations will be seen in the thermal emission from these grains. Conventional techniques which might detect such variations include measurements of broad-band infrared colors and also narrow-band spectrophotometry in the 8-14μ region. Forrest, Gillett, and Stein (1975) have reported such measurements on o Ceti and several other long-period variables. They found no evidence for large changes in the strength of emission from circumstellar material. The work reported in this Letter shows that there are changes in the dust grain emission which can be seen using rather different techniques. These variations are consistent with the limits set by Forrest, Gillett, and Stein.

Interferometric techniques in the infrared may be used to determine directly the relative brightness of circumstellar emission with respect to the stellar continuum and also the sizes of these regions of circumstellar emission (Sutton et al. 1977; McCarthy, Low, and Howell, 1977). For this, wavelengths near 11 microns are of particular importance due to the spectral feature attributed to silicate grains. Spatial resolutions of existing instruments at this wavelength are of the order of 1" which is an appropriate scale for examining many circumstellar dust shells. It is thus possible to examine variations in thermal emission from dust around long-period variables in more detail than previous techniques have allowed.

II OBSERVATIONS

The interferometer used in these observations makes use of the

McMath auxiliary telescopes at Kitt Peak National Observatory.** The equipment and techniques used have been described by Sutton et al. (1977). During these observations the sensitivities of the heterodyne receivers were approximately 3×10^{-15} watts/$\sqrt{Hz}$ for an infrared bandwidth of 0.1 cm^{-1} at 11.106μ.

Observations were made of ο Ceti from February 1977 through February 1978, which represents slightly more than one cycle of the visible light curve. No observations were possible for several months before and after May 1977 during which time ο Ceti was in the daytime sky.

The overall instrumental calibration, originally based on laboratory measurements, was verified by observing the star α Her which has been seen to have no significant silicate emission (Merrill and Stein, 1976). Thus α Her should behave as a point source since its diameter is at least an order of magnitude smaller than 0.4", which was the finest lobe spacing used. Three observations were made yielding an average fringe visibility of 0.95 ± 0.08. Since this result was consistent with unit visibility, no further correction was applied to the visibility scale. As a secondary standard, α Ori was observed with maximum resolution within a few days of each observation of ο Ceti. The observations of α Ori were internally consistent.

Figure 1 presents the measured fringe visibilities for ο Ceti. The phase quoted is with respect to the visible light curve with $\phi = 0$ representing maximum light. Note that Figure 1c contains data from two separate cycles but at nearly the same phase. Figure 2 shows a comparison set of observations on α Ori which indicate the flatness of the instrumental response.

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III RESULTS

The observations have been fitted with a two-component model of the brightness distribution in which one component is spatially unresolved and emits a fraction, f, of the flux at 11μ. The other component, which contains the remaining 1-f of the flux, was assumed to have a Gaussian spatial distribution with a full-width to 1/e intensity given by the parameter θ_g. The curves drawn in Figure 1 are the best fits to the data using this model, and the values of f and θ_g used to make these fits are listed in Table 1.

This two-component model was chosen because it was known that there would be contributions to the 11μ flux both from the stellar continuum and from dust grain emission. The diameter of the photosphere of o Ceti is sufficiently small that the region of stellar continuum emission should appear point-like at these resolutions (Labeyrie et al., 1977). This is demonstrated by the flatness of the visibility curves in Figure 1 at high resolution. The component representing dust grain emission was arbitrarily assumed to have a simple Gaussian spatial distribution. None of the results presented here are greatly affected by the detailed shape of this distribution.

The most noticeable variation shown in Table 1 is in the parameter f. Since 1-f is the fraction of the 11 micron flux contributed by dust emission, it is seen that this dust emission is strongest relative to the stellar continuum near a phase of 0.10 or slightly later. This phase also corresponds to maximum stellar luminosity indicating that the dust grain temperatures are raised by the increased stellar radiation.

The data in Table 1 also suggest some variation in the spatial extent of the region of circumstellar dust emission. The diameter, θ_g, seems to increase together with the strength of dust emission, indicating that it also may be related to the increased stellar luminosity.

Changes in stellar luminosity may be caused by changes in either effective temperature or size. The effective temperature of o Ceti is thought to undergo a periodic variation from about 2300 K to 2800 K (Strecker, 1973). This alone predicts a factor of 2.2 change in the total stellar luminosity. Small diameter changes may also be present, but Strecker calculates that the luminosity change is still about a factor of 2.2. Although this calculation is subject to a number of uncertainties, it is in good agreement with the factor of 2.5 variation in bolometric magnitude observed by Pettit and Nicholson (1933). The maximum in luminosity as well as the maxima of the 3.5μ and 11μ light curves fall at a phase of approximately 0.15 after visible maximum. Thus the changes in luminosity are of the correct phase to explain the variations in dust grain emission.

The strength of dust emission at 11 microns relative to the stellar continuum is seen from Table 1 to vary by a factor of 1.8. As the stellar temperature varies from 2300 K to 2800 K, the 11 micron stellar continuum will itself increase by a factor of 1.3. Thus, the overall change in dust emission is a factor of 2.3. This is to be compared with the calculated effect of changes in stellar luminosity on the strength of dust emission.

The expected magnitude of the variation in dust emission depends on the temperature of the grains. It is likely that emission is seen from dust at a variety of distances from the star and hence at a variety of temperatures. The maximum temperature present is limited by the condensation temperature of the grains, which is approximately

1000 K for silicate materials (Salpeter, 1977). The actual temperature of the hottest grains may be considerably lower if grain formation is inhibited due to difficulties in nucleation. The lowest temperature of interest is 250 K since dust grains cooler than this will not radiate strongly at 11μ. Grains at 1000 K and 250 K will change in brightness by factors of 1.4 and 2.6 respectively when subjected to a factor of 2.2 change in stellar luminosity. The expected variation in brightness for the entire dust shell should lie between these extremes and thus is consistent with the observed factor of 2.3 variation in dust emission. The observations further indicate that the radiation must come predominantly from grains near the cooler end of this range of temperatures.

Detailed calculations have been made for the brightness variation of an optically thin dust region using several models. It was assumed that the dust region has an inner radius characterized by some maximum temperature for grains in radiative equilibrium and that the dust density follows a power-law distribution, r^{-n}, outside of this radius. For grains with a $1/\lambda$ emissivity spectrum and a maximum temperature of 1000 K a power-law given by $n = 1.5$ is needed to produce the observed variation. This particular result does not depend strongly on the dust spectrum. The more likely density dependence $n = 2$ requires a lower maximum temperature between 500 K and 700 K. Models with grain density dropping off slower than $r^{-1.5}$ or with still lower temperature dust are ruled out in all cases since the emphasis on cooler grains would produce variations in the 11μ shell brightness with stellar phase much larger than those observed.

The observed shell diameter allows a rough determination to be made of the grain emissivity spectrum. The temperature of grains at the inner boundary of the shell has been shown to be between 500 K and 700 K. The grain emissivity spectrum determines the distance from the star at which the grains will be in equilibrium at this temperature. The observed diameter of 0.7″ fits the brightness distribution of a model with an emissivity spectrum of approximately $1/\lambda$.

The diameter of the shell appears to change somewhat with stellar phase. Such a change is the result of the fact that the cool grains change 11μ brightness faster than hotter grains as the stellar luminosity increases. Thus emission at larger distances from the star is emphasized as the dust is heated. The model with a maximum grain temperature of 500 K to 700 K, an r^{-2} density dependence, and a λ^{-1} grain emissivity spectrum predicts a 20% increase in diameter from minimum to maximum stellar luminosity. This increase is consistent with the observed variation within the rather large errors. This apparent size change need not involve any physical redistribution of the dust itself. Such redistribution is possible although unlikely within the timescales involved here.

The optical depth of the dust shell can be derived from the brightness of the circumstellar shell, but it is dependent on all of the parameters of the model. The result for the model indicated here is an optical depth at 11 microns of approximately 0.02.

Since the properties of this dust model depend rather strongly on the observed variation in dust brightness, it is important to consider other more conventional measurements which may be able to detect this variation. For example, the 8-14μ spectrum of o Ceti should show a more pronounced silicate emission feature at phases near maximum luminosity. Such a variation is suggested in the data of Forrest, Gillett, and Stein (1975). However, this should be interpreted with caution since their single spectrum near maximum light predated their other spectra by several years. In addition, it is possible that such spectra may have been distorted due to phase-dependent changes in the strength of SiO absorption bands at 8μ such as those changes detected by Hinkle et al. (1976) in the first overtone bands of SiO at 4μ. If so, as maximum light was approached the 8μ absorption may have weakened at the same time as silicate emission near 11μ was getting stronger. Thus the shape of the spectrum over this narrow region may have remained relatively unchanged. Nevertheless, further investigation of the 8-14μ spectra of long-period variables at various phases may prove fruitful.

Broadband infrared color measurements provide additional information. The observations of Forrest, Gillett, and Stein show a variation of approximately 0.2^m in [11μ] - [8.4μ] with the 11μ band being relatively brightest at phases between 0.0 and 0.25. As with the spectrophotometric measurements the effect of SiO absorption near 8μ may be such as to mask an inherently much larger variation in [11μ] - [8.4μ]. Similarly the quantity [11μ] - [3.5μ] is contaminated by the H_2O absorption band at 2.7μ. Forrest, Gillett, and Stein observed virtually no variation in this color as a function of phase. Yet considering the 1.3^m amplitude of the 2.7μ light curve observed by Maran et al. (1977) and the width of the absorption in this region as shown by the data of Merrill and Stein (1976), it is to be expected that there would be a variation in [3.5μ] of approximately 0.3^m solely due to changes in H_2O absorption. This effect masks variations in [11μ] - [3.5μ] which may be present due to increased dust emission. Thus the broadband photometric measurements are consistent with the observed increased dust emission at phases near 0.10 although by themselves they are not sufficient to demonstrate such an increase.

IV SUMMARY

The observed variations in the 11 micron brightness distribution of o Ceti indicate an increase in both the relative brightness and the apparent size of the circumstellar dust shell occurring during the period of maximum stellar luminosity. These variations can be understood in terms of changes in the temperature of the dust grains produced by the known variation in luminosity of o Ceti.

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TABLE 1

PARAMETERS USED TO FIT FRINGE VISIBILITY MEASUREMENTS

Figure	Phase	f	θ_g
1a	0.75	0.54 ± 0.02	*
1b	0.90	0.54 ± 0.02	$0\overset{\prime\prime}{.}62 \pm 0.08$
1c	0.11	0.40 ± 0.01	$0\overset{\prime\prime}{.}77 \pm 0.14$
1d	0.24	0.48 ± 0.02	$0\overset{\prime\prime}{.}79 \pm 0.12$

* Undetermined due to the lack of measurements at low spatial resolution.

FIGURE CAPTIONS

Figure 1: Fringe visibility measurements of o Ceti at 4 different phases of its light cycle. Curves drawn are fits using the parameters of Table 1 as discussed in the text. The graphs are in order of increasing phase centered about $\phi = 0$.

Figure 2: Comparison fringe visibility measurements for α Orionis.

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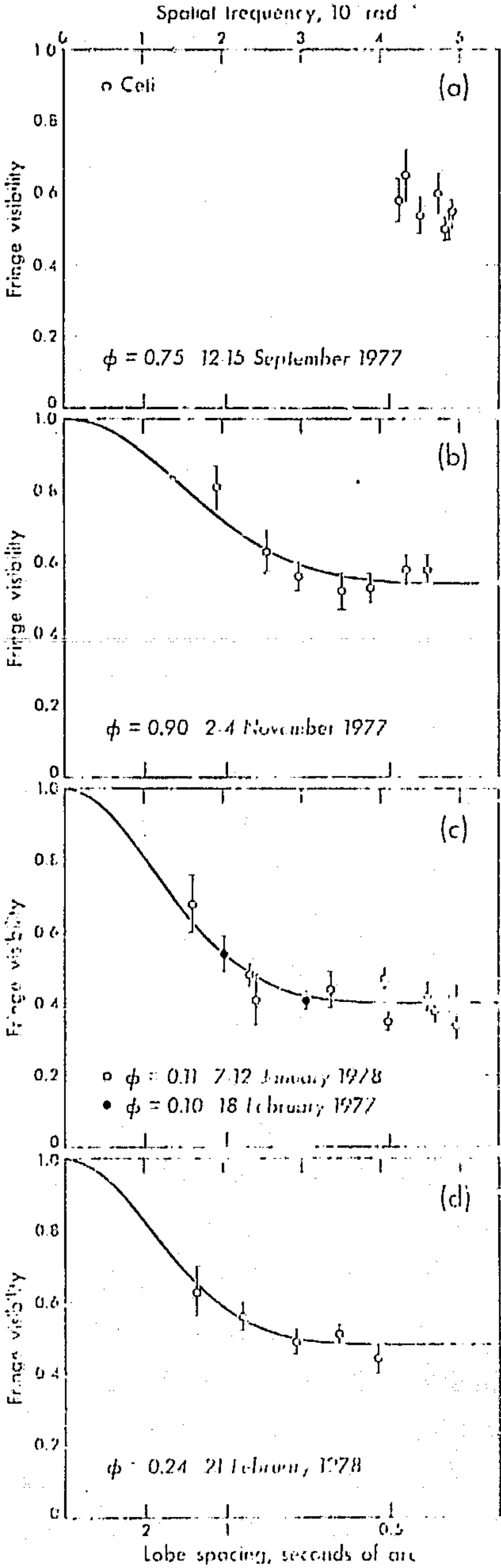
Spatial frequency, 10 rad
(a)
o Ceti
Fringe visibility
φ = 0.75 12-15 September 1977
(b)
φ = 0.90 2-4 November 1977
(c)
φ = 0.11 7-12 January 1978
φ = 0.10 18 February 1977
(d)
φ = 0.24 21 February 1978
Lobe spacing, seconds of arc

Figure 1

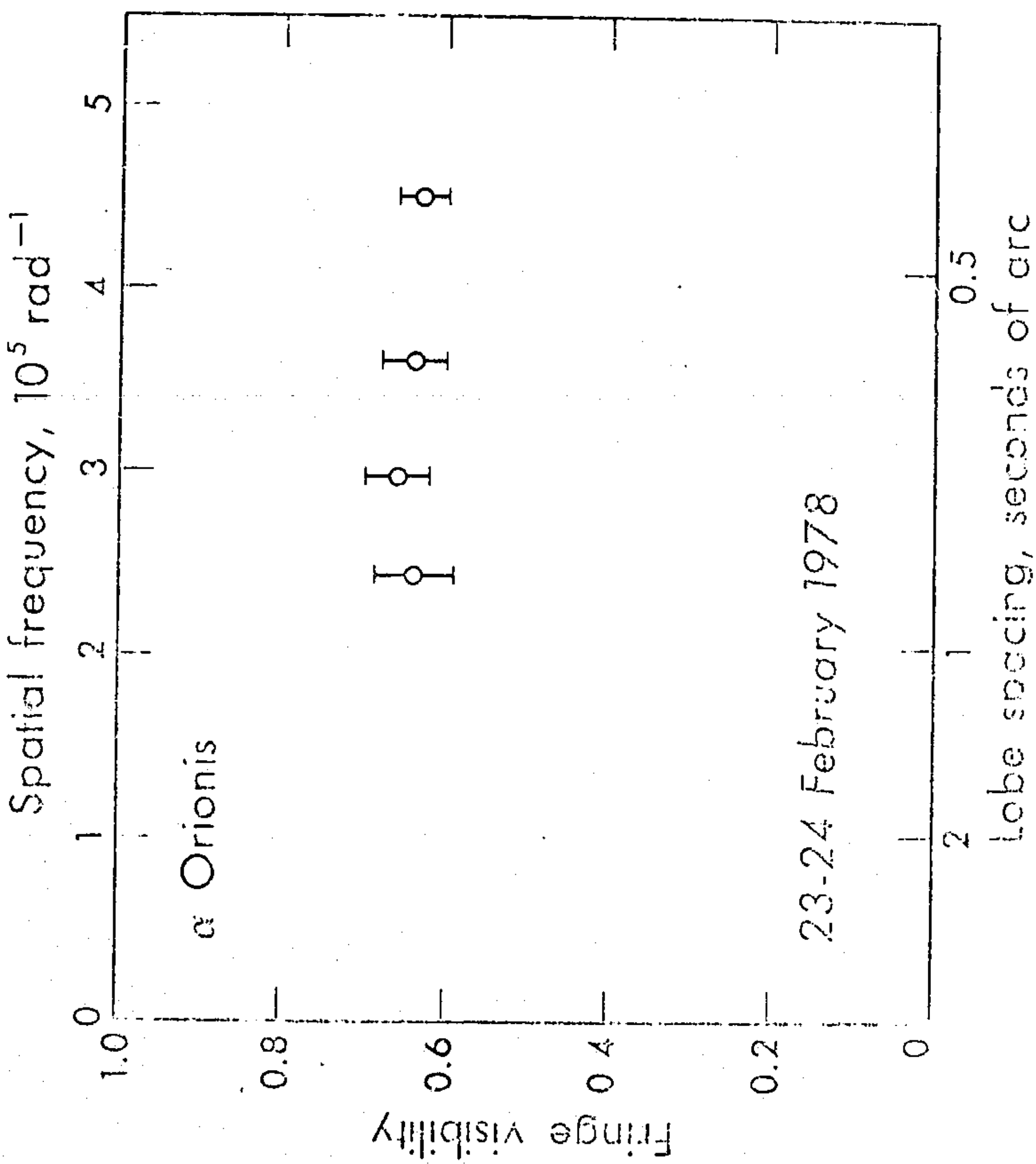
Spatial frequency, 10^5 rad^{-1}
0
1
2
3
4
5
α Orionis
23-24 February 1978
Lobe spacing, seconds of arc
2
1
0.5
Fringe visibility
1.0
0.8
0.6
0.4
0.2
0

Figure 2