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SPATIAL HETERODYNE INTERFEROMETRY OF VY CANIS MAJORIS, ALPHA ORIONIS, ALPHA SCORPII, AND R LEONIS AT 11 MICRONS*

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ABSTRACT

Using the technique of heterodyne interferometry, measurements have been made of the spatial distribution of 11 micron radiation from four late-type stars. The circumstellar shells surrounding VY CMa, α Ori, and α Sco were resolved, whereas that of R Leo was only partially resolved at a fringe spacing of 0″.4.

Subject headings: infrared: general — interferometry — stars: circumstellar shells

I. INTRODUCTION

Circumstellar dust shells around late-type stars in many cases emit large amounts of radiation near 10 microns in excess of that contributed by the central stars. Woolf and Ney (1969) suggested that this excess is characteristic of thermal emission from silicate grains. Other evidence for the existence of circumstellar dust grains has been found in measurements of the intrinsic polarization of visible light from these stars (Dyck *et al.* 1971; Forrest *et al.* 1975). Although work has been done to predict the density and temperature distribution of this dust (Dyck and Simon 1975), more experimental results which measure these properties are needed.

In this *Letter* observations are presented which directly measure the spatial distribution of radiation at 11 microns for VY CMa, α Ori, α Sco, and R Leo. This is the first use of heterodyne techniques with separate telescopes for stellar interferometry in the infrared. Preliminary results of this work for the first two sources have been discussed by Sutton *et al.* (1976), and non-heterodyne, single-telescope measurements at somewhat lower resolution on a number of infrared sources have been reported by McCarthy, Low, and Howell (1977).

II. OBSERVATIONS

Observations were made between 1976 October and 1977 February at Kitt Peak National Observatory[1] using the twin McMath auxiliary telescopes as elements of a spatial interferometer. These telescopes provided 81 cm apertures separated by a 5.5 m east-west baseline. The interferometer was similar to that described by Johnson, Betz, and Townes (1974) and Johnson (1974) except for a factor of 5 improvement in sensitivity due to the use of HgCdTe photodiode detectors (Spears 1977). A detector mounted at each telescope operated as a heterodyne receiver using a CO_2 laser local oscillator, and the two detected outputs were correlated electrically. All observations were made at a central wavelength of 11.106 μm and with an infrared bandwidth of approximately 0.1 cm^{-1}. The receivers each had a sensitivity of approximately 5×10^{-15} W after a 1 second integration period, corresponding to an effective system quantum efficiency of 0.2.

For each source, fringe visibilities were measured over the range of spatial frequencies made possible by the foreshortening of the interferometer baseline as the hour angle of the source changed. Highest spatial resolution for each source occurred at the time of transit and corresponded to a spacing of 0″.4 between lobes of the interference pattern. The coarsest lobe spacing at which observations could be made without looking too near the horizon was determined by the declination of the source. Only for VY CMa were such observations attempted very near the horizon. Typically a measurement consisted of a 1000 or 2000 s integration on the interference signal, preceded and followed by calibration measurements of the source intensity in each telescope separately. The fringe visibility is simply the amplitude of the interference signal normalized to these single-telescope signals.

The data discussed in the following sections are presented in Figures 1 through 4. Error bars are $\pm\sigma$ and represent statistical errors only. The determination of the fringe visibility scale relies on the internal calibration of the instrument since none of the brightest 11 μm sources was deemed, *a priori*, to be a suitable point source. The accuracy of this calibration is estimated to be better than 10%. In the case of α Ori, the

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visibilities determined are in reasonable agreement with the independent measurements of McCarthy, Low, and Howell (1977), who report visibilities of 0.76 at lobe spacings of 1″.14 and 0″.76. This is the only source for which a direct comparison with these authors' data can be made.

a) *VY Canis Majoris*

Herbig (1970b) has described VY CMa as an M3–5 star surrounded by an optically thick shell of dust. In his model the shell extends to a diameter of 2″ about the central source, with dust temperatures near 1700 K on the inside of the shell and 350 K on the outer surface. The optical depth in the silicate feature is not known, so a detailed prediction of the distribution of radiation at 11 μm cannot be made. The interpretation of the geometry of this source is further complicated by the suggestion (Herbig 1970*a;* Snyder and Buhl 1975; Van Blerkom and Auer 1976) that the gas and dust are confined to a rotating disk. This suggestion was made in order to explain the multiple components of SiO maser lines in the radio region.

The data in Figure 1 show that VY CMa is resolved at fringe spacings between 0″.40 and 0″.65. If a uniform circular emitting region is chosen as a simplified model for the flux distribution, the present data can be fitted with a shell diameter of 0″.60 ± 0″.05. However, this interpretation does not agree with the measurement of McCarthy, Low, and Howell (1977) within their stated errors, nor does it fit the present data particularly well. On the other hand, the diameter of 0″.78 ± 0″.04 given by McCarthy, Low, and Howell, also for a uniform circular intensity distribution model, predicts visibilities lower than those seen in these present measurements at higher spatial frequencies. A circular model of uniform brightness is thus inadequate to explain the observations. Since the dust shell should gradually become cooler and optically thinner with increasing radius, a more tapered form of the brightness distribution is likely. For example, a simple Gaussian intensity distribution fits the data better than a uniform circular distribution. The data reported here, together with those of McCarthy, Low, and Howell, are fitted by a Gaussian flux distribution whose full width to 1/*e* intensity is 0″.58 ± 0″.04 and which is augmented by an unresolved component containing 8% of the flux. There are other distributions which are possible, but differentiation between more complex radial distributions or models which are not spherically symmetric will require further observations.

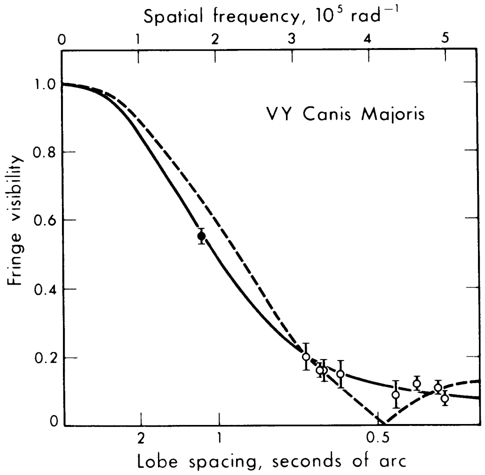

FIG. 1.—Fringe visibility plot for VY Canis Majoris. *Open circles,* measurements reported in this *Letter*; *filled circle,* from McCarthy, Low, and Howell (1977). *Dashed curve,* the fringe visibility expected for a uniform circular disk 0″.6 in diameter. *Solid curve,* a Gaussian flux distribution with 0″.58 full width to 1/*e* intensity containing 92% of the flux, with the remainder in an unresolved component.

b) *Alpha Orionis*

Alpha Orionis is an M2 supergiant whose circumstellar material has been extensively studied. Bernat and Lambert (1975) have observed the gas shell of α Ori out to distances of 100 R_*. In addition, the infrared photometry has been interpreted by Dyck and Simon (1975) in terms of a dust shell extending to 250 R_*. But many details are still lacking, such as the conditions necessary for the formation of circumstellar grains and hence their likely distribution.

It is known from the broad-band photometric measurements reported by Gillett, Merrill, and Stein (1971) and Dyck *et al.* (1971) that α Ori is 1 magnitude brighter at 11 μm than at 3.5 μm. Assuming the photosphere of α Ori is at a temperature of 3250 K, this excess indicates that 55% of the flux at 11 μm represents photospheric emission and the remaining 45% is contributed by circumstellar material. This ratio is confirmed by spectrophotometric observations in the 11 μm region (Merrill and Stein 1976).

The data presented in Figure 2 show a visibility of

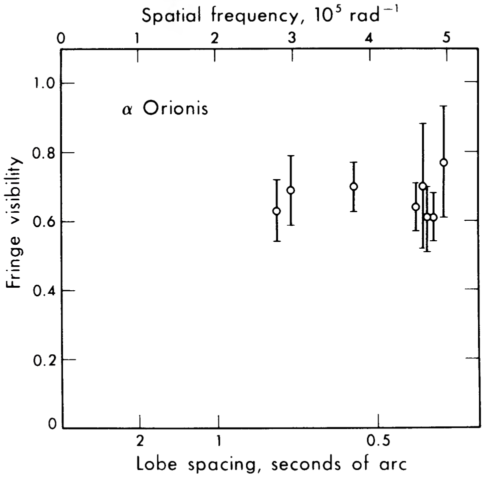

FIG. 2.—Fringe visibility measurements for α Orionis

65% for α Ori with essentially no variation for fringe spacings between 0″.41 and 0″.76. If a diameter of 0″.05 is adopted for the photosphere of α Ori (Bonneau and Labeyrie 1973; Currie, Knapp, and Liewer 1974; Lynds, Worden, and Harvey 1976), the flatness of the visibility curve indicates that less than 20% of the excess circumstellar radiation at 11 μm is emitted by material between 6 R_* and 12 R_* from α Ori. The discrepancy between the observed visibility and the predicted photospheric contribution is comparable to the errors assigned to these quantities, indicating that the dust shell may be fully resolved in these measurements.

If any dust were present within 12 R_* of α Ori it would be at relatively high temperature and therefore would contribute strongly to the radiation at 11 μm. At this distance the equilibrium temperature of a blackbody grain is approximately 700 K, which is cooler than the temperature generally assumed to be necessary for the condensation of grains (Gilman 1969). Thus, although the outflowing circumstellar material may have begun to form dust grains close to the star, the density of grains is still rather low out to 12 R_*.

c) Alpha Scorpii

Alpha Scorpii is an oxygen-rich supergiant similar to α Ori in spectral type and luminosity class. However, it has a weaker silicate emission feature accounting for only 30% of the total flux at 11 μm (Merrill and Stein 1976). The data in Figure 3, though limited, are sufficient to show that this dust shell is also resolved at fringe spacings of 0″.4. The dust is found to exist outside of 12 R_* from α Sco, as was the case also for α Ori.

d) R Leonis

R Leonis is a late-type Mira variable with a photospheric temperature of approximately 2400 K. Visible diameters for the photosphere have been reported which range from 0″.03 to 0″.07 (Blazit *et al.* 1977; Nather and Wild 1973). The silicate excess in this source accounts for 35% of the 11 μm flux (Merrill and Stein 1976).

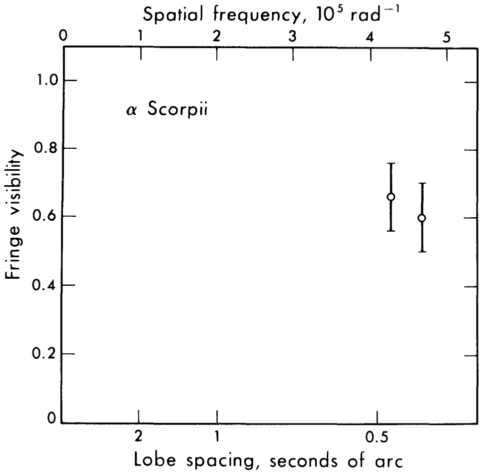

FIG. 3.—Fringe visibility measurements for α Scorpii

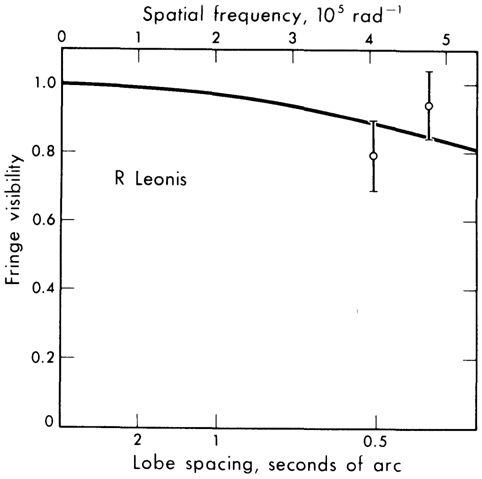

FIG. 4.—Fringe visibility measurements for R Leonis. *Solid curve*, the fit to a uniform dust shell 0″.28 in diameter contributing 35% of the flux, with the remainder in an unresolved component.

The data in Figure 4 show that, in contrast to α Ori and α Sco, much of this excess emission remains to be resolved. The data are fitted by a uniform circular shell of diameter 0″.28 ± 0″.09, contributing the 35% of the flux corresponding to the silicate excess. Although the errors on this measurement are large, the result is in reasonable agreement with the diameter of 0″.34 ± 0″.09 for the silicate shell previously determined by Neugebauer *et al.* (1972) and Zappala (1977).

This diameter implies that the silicate emission comes predominantly from material within about 5 R_* from R Leo. For α Ori and α Sco a lower limit of 12 R_* was set for the distance to the emitting region. It is likely that this difference is related to the lower temperature of R Leo which enables the grains to condense, on the average, closer to the star.

III. SUMMARY

The circumstellar dust shells around the sources reported in this *Letter* are seen to have quite different characteristics. The shell around VY CMa is optically thick and has been well resolved; most of the radiation can be modeled by a Gaussian intensity distribution with full width to 1/*e* intensity of 0″.58. The remaining three sources are surrounded by optically thin dust, at different distances from the central star. The coolest star, the Mira variable R Leo, emits the majority of its excess 11 μm radiation near 5 R_*, while the supergiants α Ori and α Sco emit the majority of their excess from outside of 12 R_*.

The use of spatial heterodyne interferometry to successfully measure the sizes of circumstellar dust shells demonstrates the potential of this technique for examining at high resolution the spatial distribution of infrared emission from stars. The resolution made possible by using two well-separated telescopes can be much greater than that possible with any single existing telescope; further measurements using this technique promise to provide detailed information about circumstellar material which would be difficult to obtain in any other way.

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