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SPATIAL HETERODYNE INTERFEROMETRY OF VY CANIS MAJORIS,
 α ORIONIS, α 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 Canis Majoris, α Orionis, and α Scorpii were resolved, whereas that of R Leonis was only partially resolved at a fringe spacing of 0.4".

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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 and 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 Canis Majoris, α Orionis, α Scorpii, and R Leonis. 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 et al. (1977).

II Observations

Observations were made between October 1976 and February 1977 at Kitt Peak National Observatory* 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, et al. (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 CO₂ laser local oscillator, and the two detected outputs were correlated electrically. All observations were made at a central wavelength of 11.106 μ 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.

* Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

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 Canis Majoris were such observations attempted very near the horizon. Typically a measurement consisted of a 1000 or 2000 second 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 11μ 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 Orionis, the visibilities determined are in reasonable agreement with the independent measurements of McCarthy et al. (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 can be made.

a) VY Canis Majoris

Herbig (1970 b) has described VY Canis Majoris 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 μ can not 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 Canis Majoris is resolved at fringe spacings between 0.40" and 0.65". If a uniform circular emitting region is chosen as a simplified model to the flux distribution, the present data can be fit with a shell diameter of 0.60" \pm 0.05". However this interpretation does not agree with the measurement of McCarthy et al. (1977) within their stated errors nor does it fit the present data particularly well. On the other hand, the diameter of 0.78" \pm 0.04" given by McCarthy et al., 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 that of McCarthy et al. are fit by a Gaussian flux distribution whose full width to $1/e$ intensity is $0.58'' \pm 0.04''$ 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.

b) α Orionis

α Ori 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 $100 R_{\star}$. In addition, the infrared photometry has been interpreted by Dyck and Simon (1975) in terms of a dust shell extending to $250 R_{\star}$. 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 broadband photometric measurements reported by Gillett et al. (1971) and Dyck et al. (1971) that α Ori is one magnitude brighter at 11μ than at 3.5μ . Assuming the photosphere of α Ori is at a temperature of 3250 K this excess indicates that 55% of the flux at 11μ represents photospheric emission and the remaining 45% is contributed by circumstellar material. This ratio is

confirmed by spectrophotometric observations in the 11μ region (Merrill and Stein, 1976).

The data presented in figure 2 show a visibility of 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 et al., 1974; Lynds et al., 1976) the flatness of the visibility curve indicates that less than 20% of the excess circumstellar radiation at 11μ 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 11μ . 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) α Scorpii

α Sco 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 11μ (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 Leo 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 $0.07''$ (Blaxit, et al., 1977; Nather and Wild, 1973). The silicate excess in this source accounts for 35% of the 11μ flux (Merrill and Stein, 1976).

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 fit by a uniform circular shell of diameter $0.28'' \pm 0.09''$ 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 $0.34'' \pm 0.09''$ 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 Canis Majoris 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 11μ 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 possible using two well-separated telescopes can be much greater than that possible on 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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FIGURE CAPTIONS:

FIGURE 1: Fringe visibility plot for VY Canis Majoris.

Open circles represent the measurements reported in this Letter and the filled circle is from McCarthy et al. (1977). The dashed curve shows the fringe visibility expected for a uniform circular disc 0.6" in diameter. The solid curve is 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.

FIGURE 2: Fringe visibility measurements for α Orionis.

FIGURE 3: Fringe visibility measurements for α Scorpii.

FIGURE 4: Fringe visibility measurements for R Leonis.

The solid curve shows the fit to a uniform dust shell 0.28" in diameter contributing 35% of the flux with the remainder in an unresolved component.

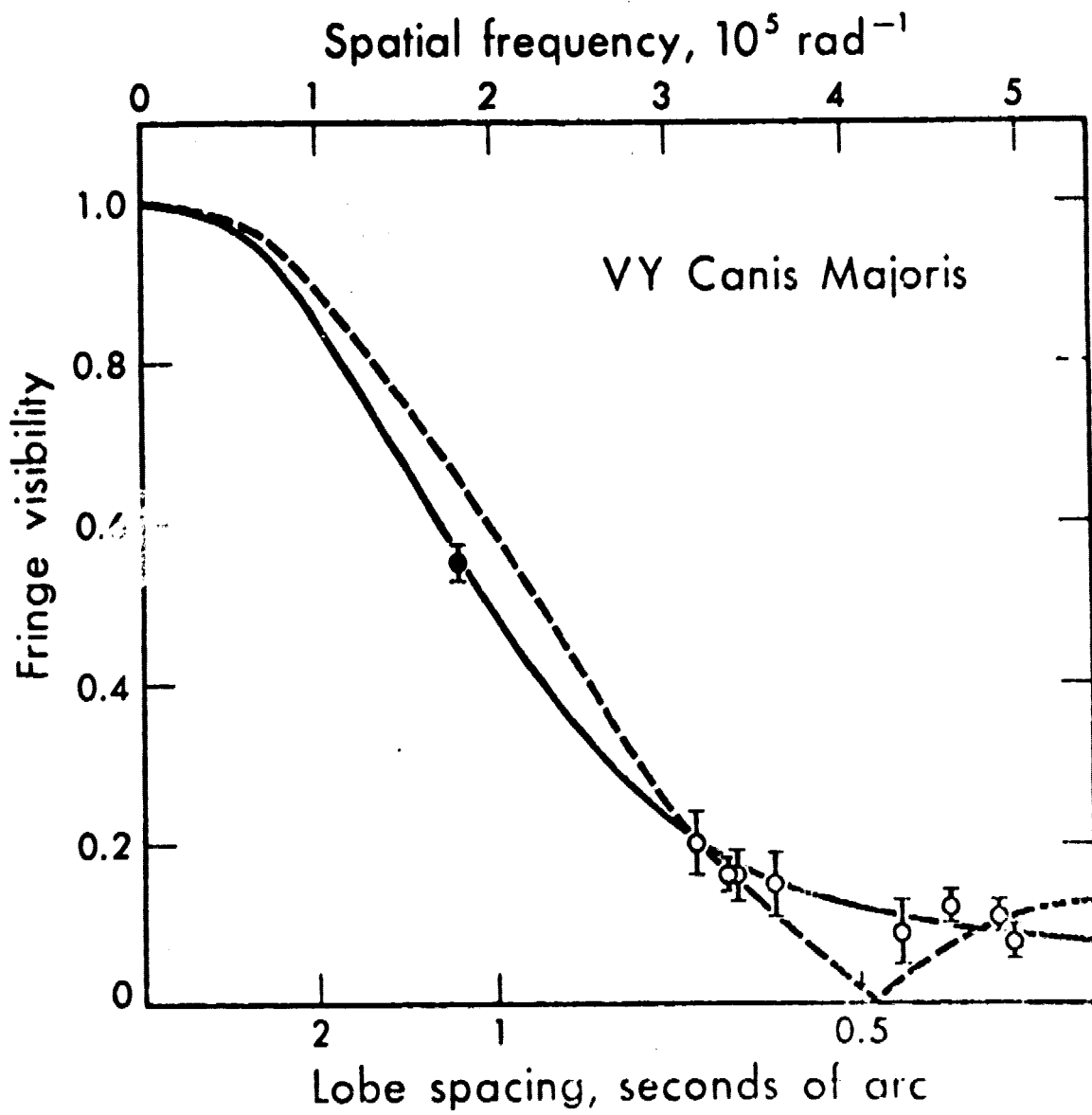


Figure 1.

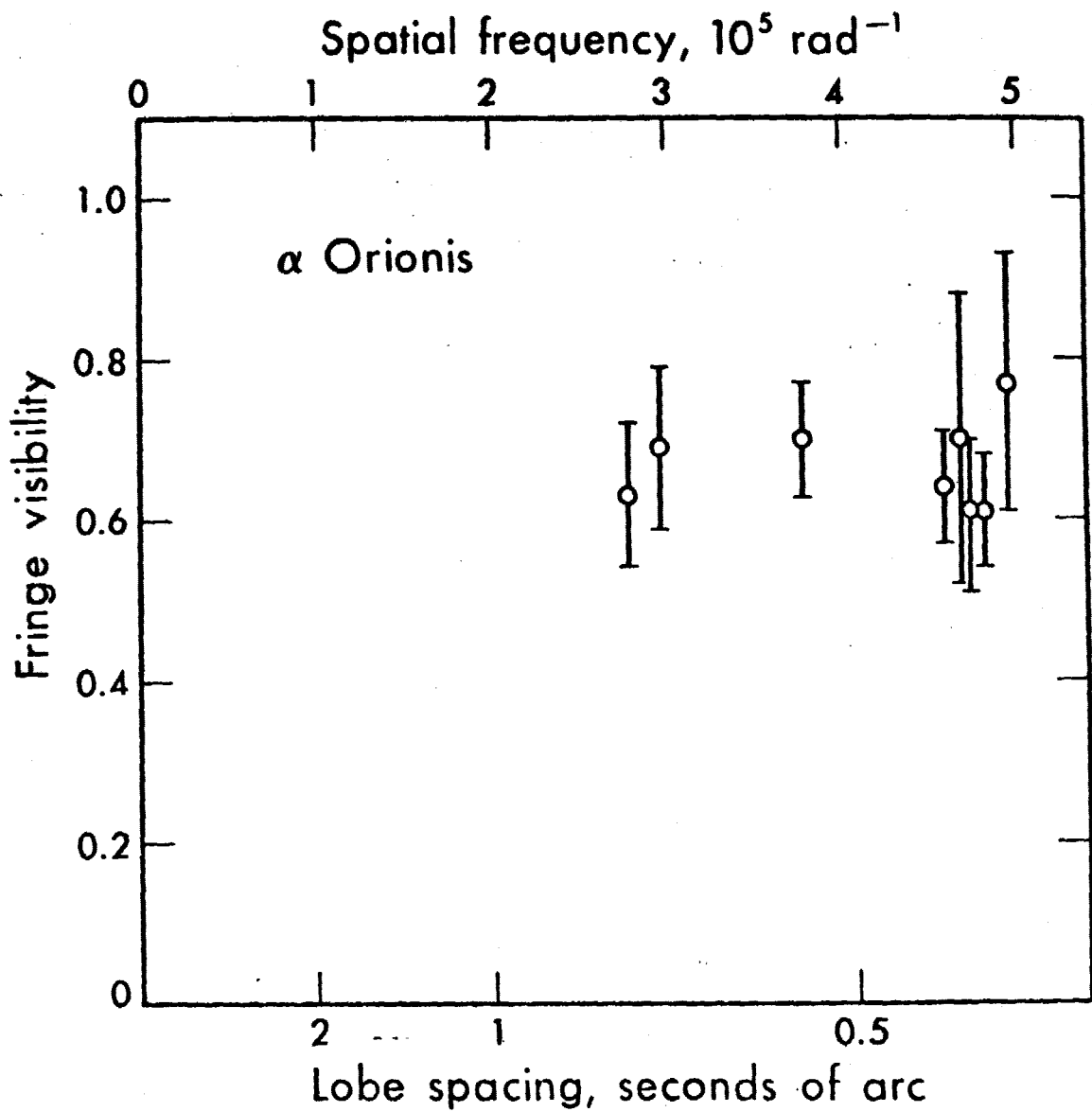


Figure 2.

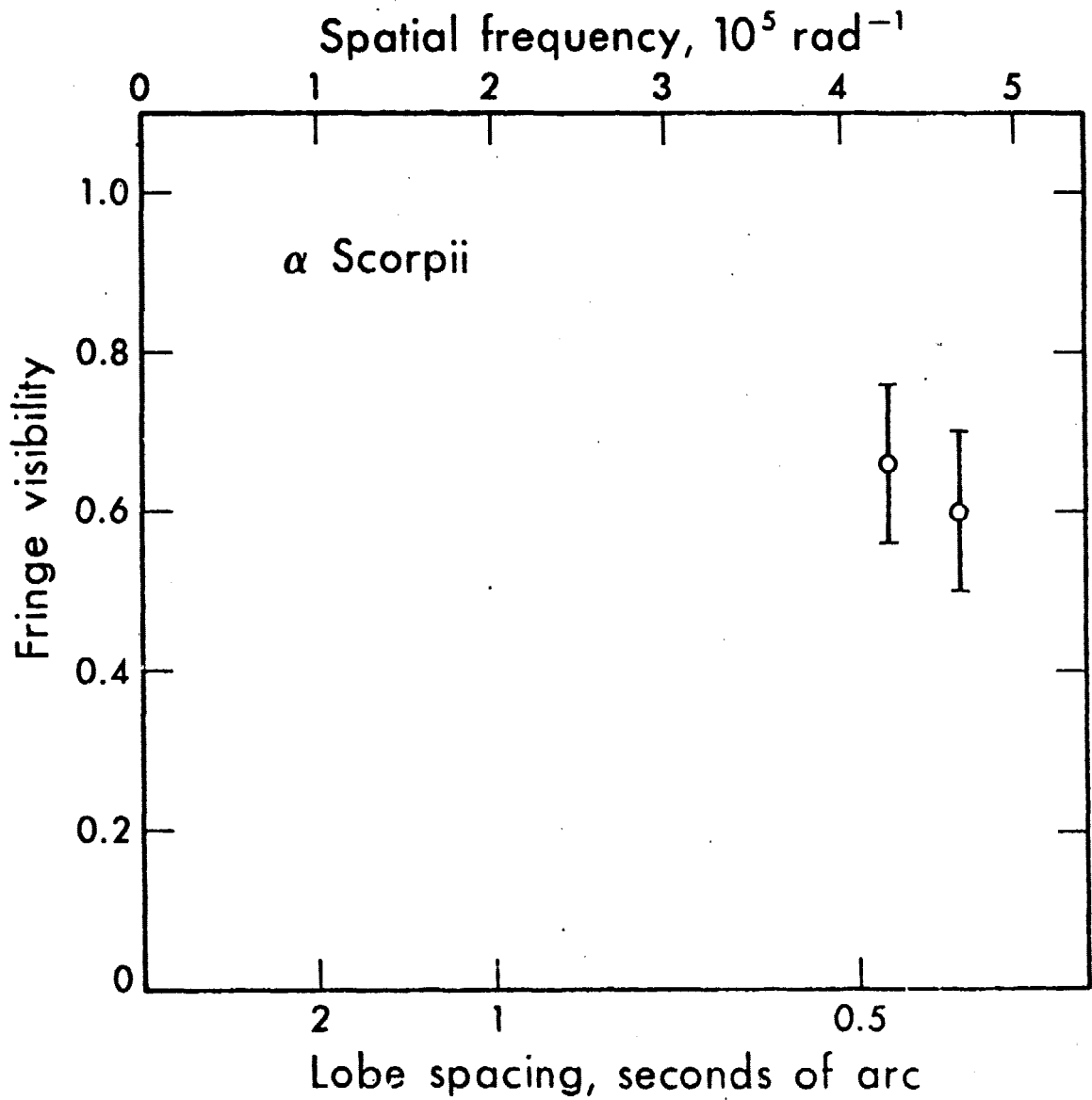


Figure 3.

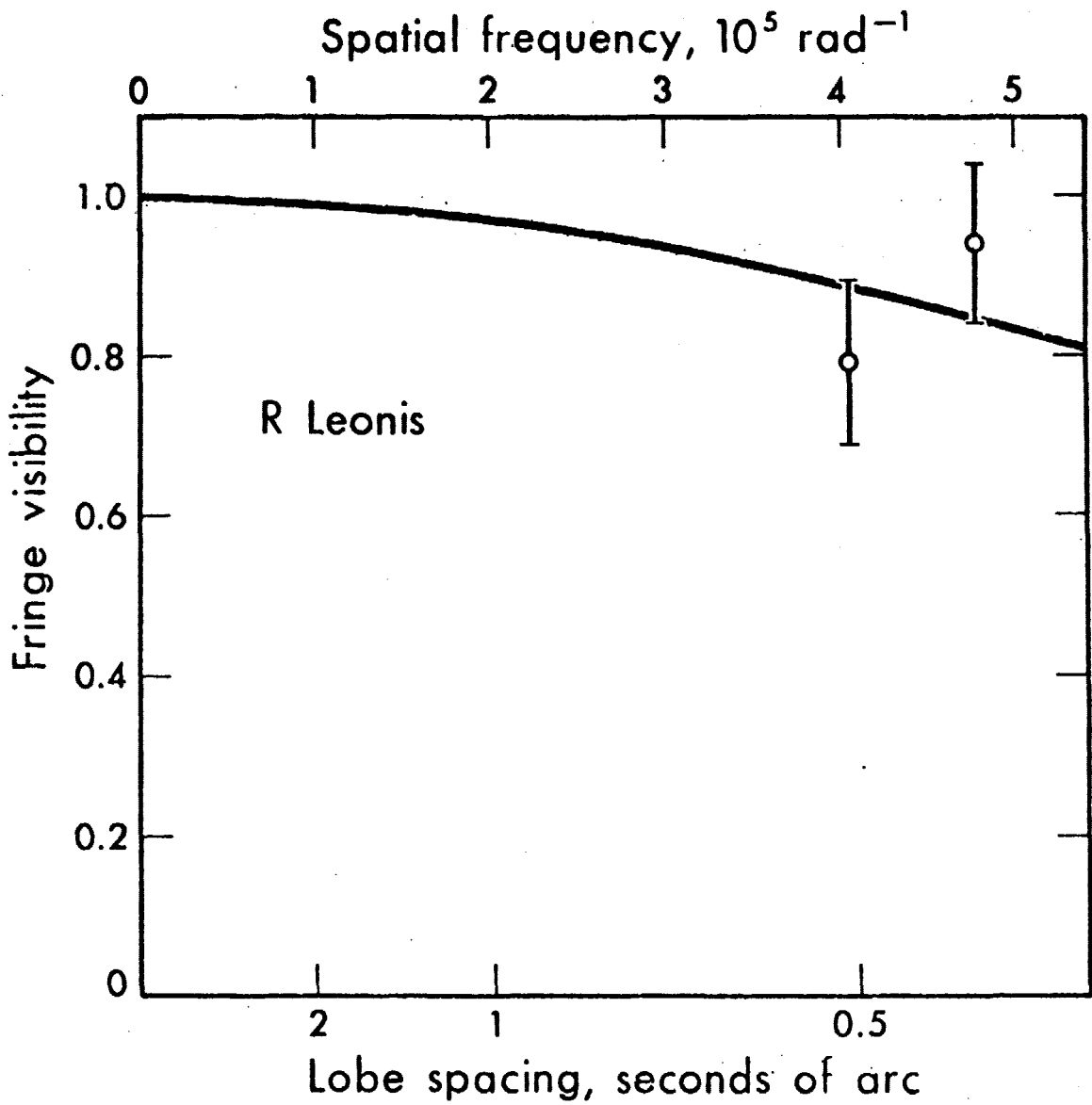


Figure 4.

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