General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.
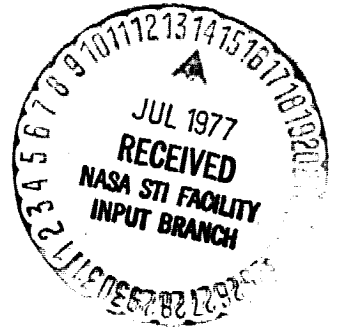
SPATIAL HETERODYNE INTERFEROMETRY OF VY CANIS MAJORIS, α ORIONIS, α SCORPII, AND R LEONIS AT 11 MICRONS*

E.C. Sutton[†], J.W.V. Storey, A.L. Betz, C.H. Townes

Department of Physics
University of California
Berkeley, California 94720

and

D.L. Spears

Lincoln Laboratory, M.I.T.
Lexington, Mass. 02173

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".

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 CO_2 laser local
oscillator, and the two detected outputs were correlated
electrically. All observations were made at a central wave-
length of 11.106 μ and with an infrared bandwidth of approxi-
mately 0.1 cm^{-1}. The receivers each had a sensitivity of
approximately 5 x 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 fore-
shortening 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 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 ± σ 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 μ 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" ± 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" ± 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" ± 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_*. 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 broadband photometric measurements reported by Gillett et al. (1971) and Dyck et al. (1971) that α Ori is one magnitude brighter at 11 μ than at 3.5 μ. Assuming the photosphere of α Ori is at a temperature of 3250 K this excess indicates that 55% of the flux at 11 μ represents photospheric emission and the remaining 45% is contributed by circumstellar material. This ratio is

confirmed by spectrophotometric observations in the 11 μ 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 11 μ 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 μ. 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 11 μ (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 11 μ
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" ± 0.09" contributing the 35% of the flux corresponding
to the silicate excess. Although the errors on this measure-
ment 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 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 11 μ 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.

the National Radio Astronomy Observatory. Finally, we
thank E. Wollman, H. Smith, and F. Baas for their assistance
in making these observations.

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 dist
            shell 0.28" in diameter contributing 35% of the
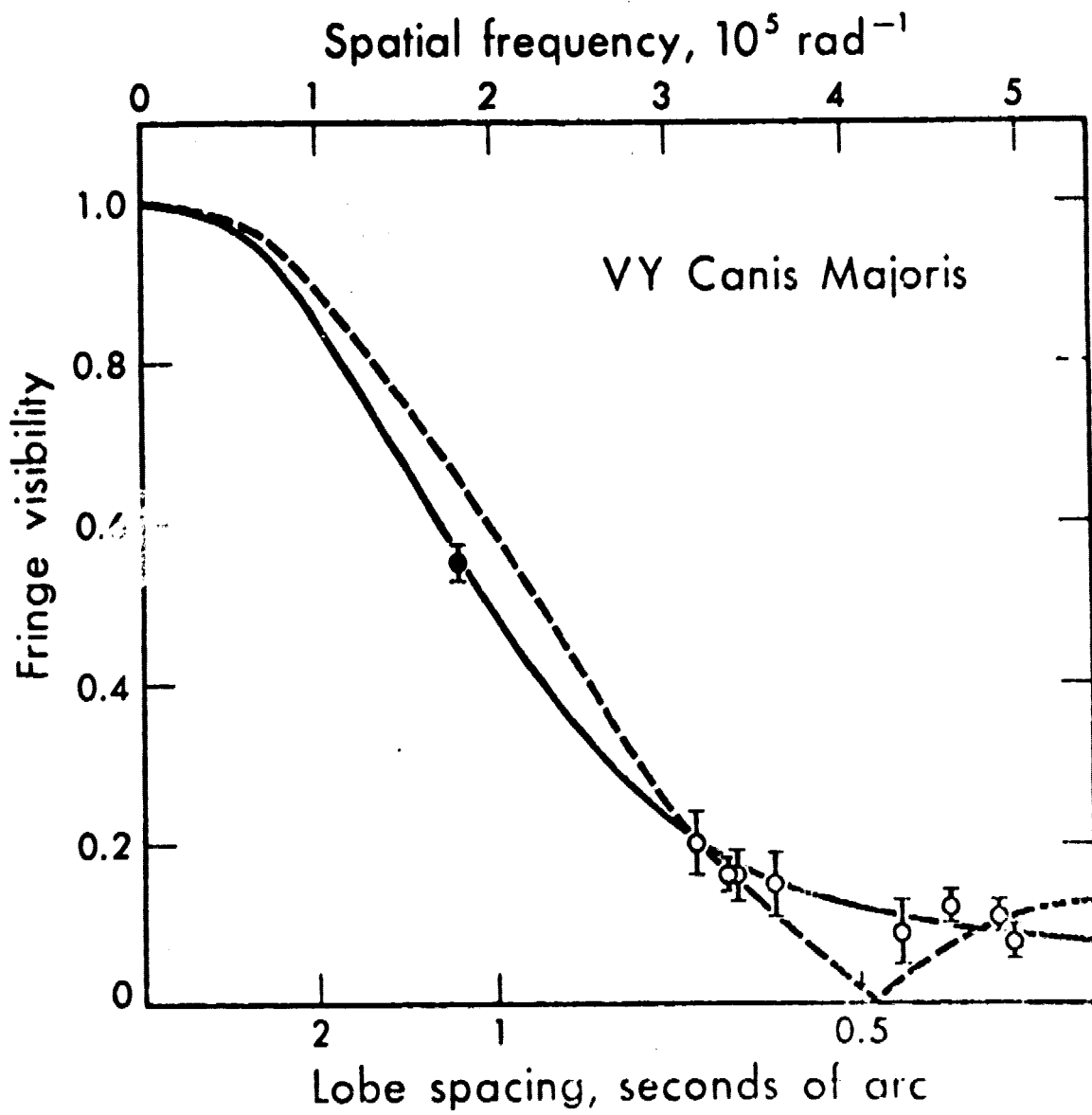   flux with the remainder in an unresolved component.
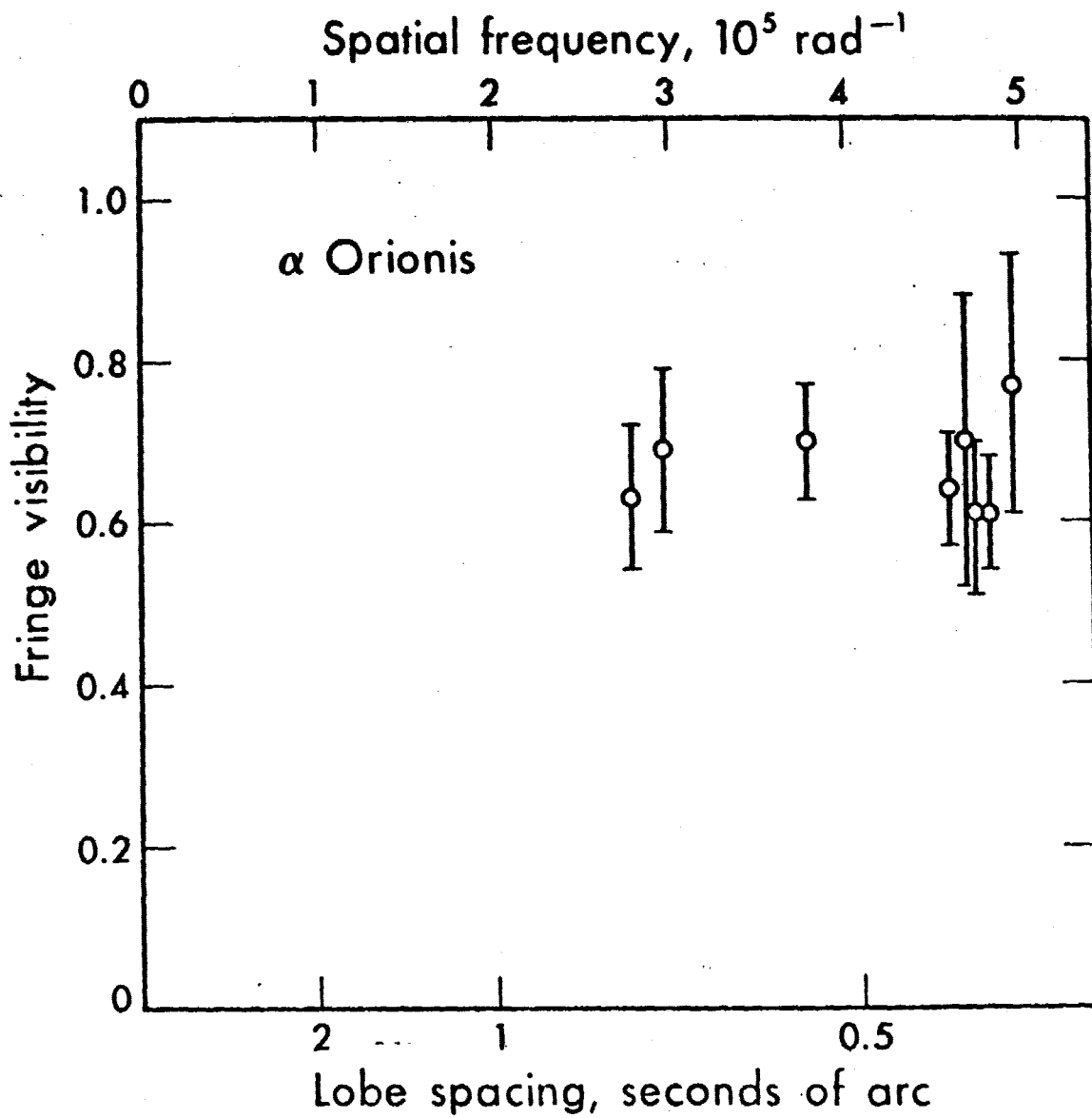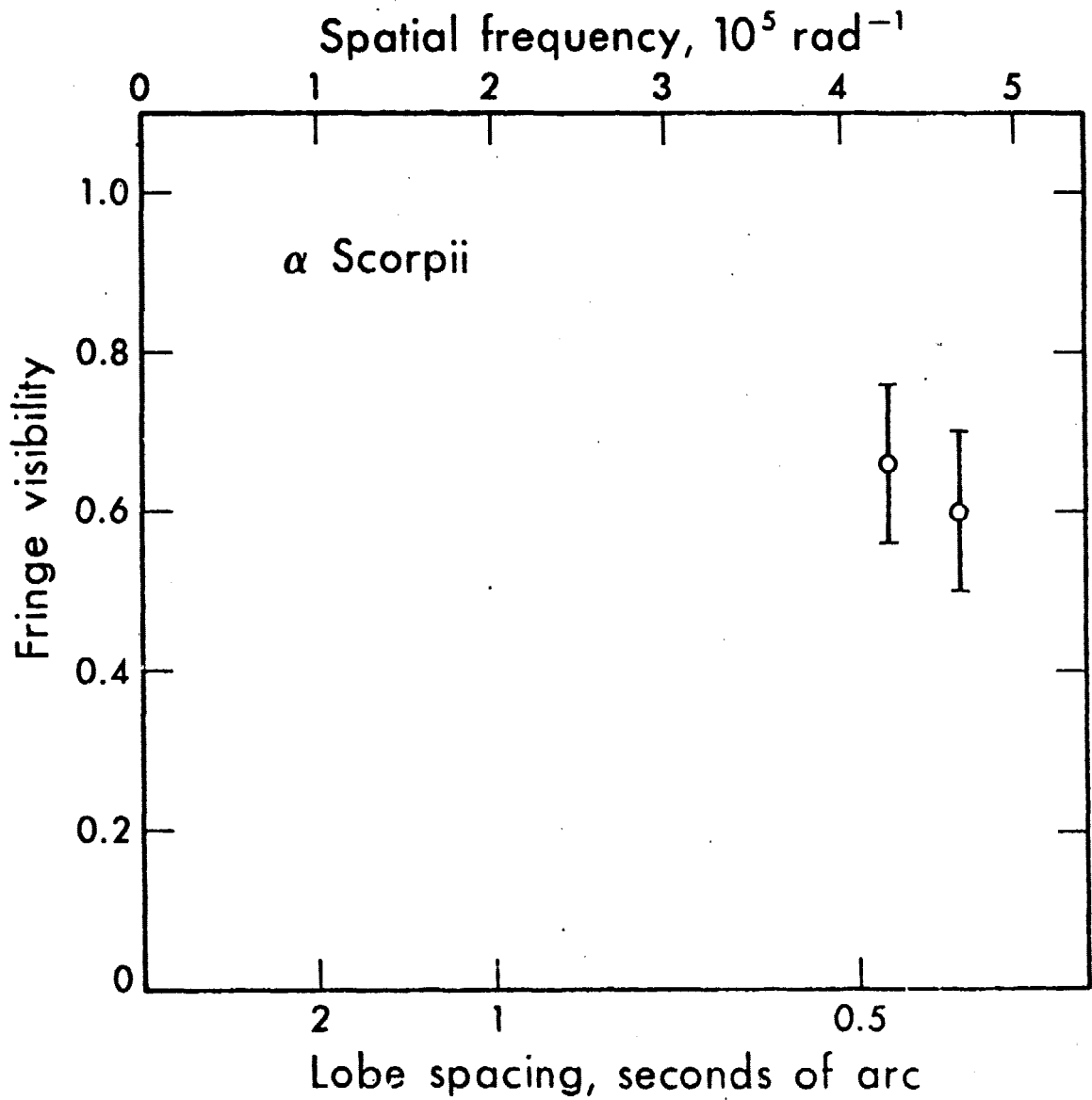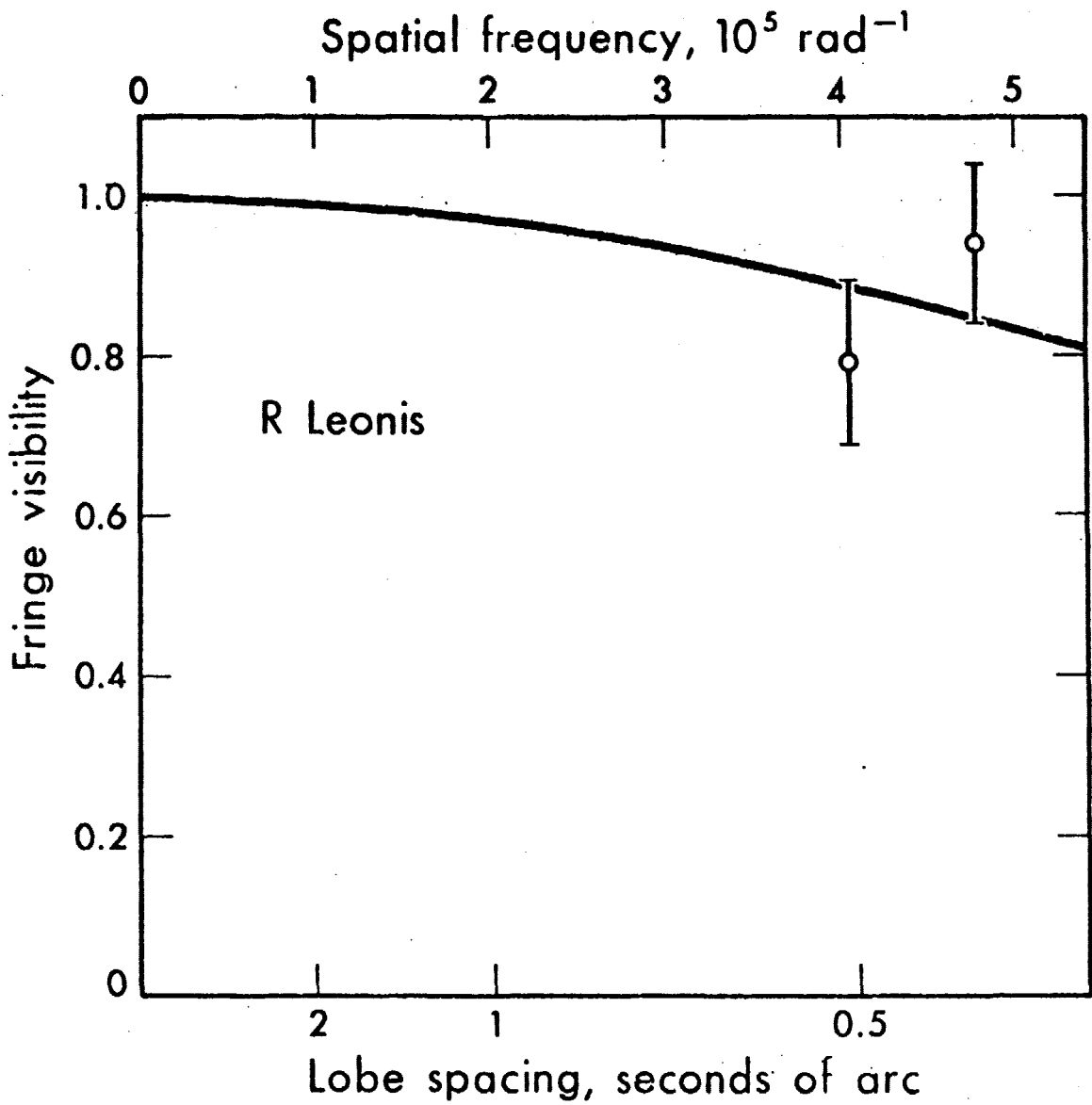
Figure 1.

Figure 2.

Figure 3.

Figure 4.

REFERENCES

Bernat, A.P. and Lambert, D.L. 1975, Ap. J. (Letters), 201, L153.

Blazit, A., Bonneau, D., Koechlin, L., and Labeyrie, A. 1977, Ap. J. (Letters), 214, L79.

Bonneau, D. and Labeyrie, A. 1973, Ap. J. (Letters), 181, L1.

Currie, D. G., Knapp, S.L., and Liewer, K.M. 1974, Ap. J., 187, 131.

Dyck, H.M., Forrest, W.J., Gillett, F.C., Stein, W.A., Gehrz, R.D., Woolf, N.J., and Shawl, S.J. 1971, Ap. J., 165, 57.

Dyck, H.M. and Simon, T. 1975, Ap. J., 195, 689.

Forrest, W.J., Gillett, F.C., and Stein, W.A. 1975, Ap. J., 195, 423.

Gillett, F.C., Merrill, K.M., and Stein, W.A. 1971, Ap. J., 164, 83.

Gilman, R.C. 1969, Ap. J. (Letters), 155, L185.

Herbig, G.H. 1970 a, Mem. Soc. Roy. Sci. Liege, 19, 13.

Herbig, G.H. 19.0 b, Ap. J., 162, 557.

Johnson, M.A. 1974, Unpublished Ph.D. Thesis, Univ. of California (Berkeley).

Johnson, M.A., Betz, A.L., and Townes, C.H. 1974, Phys. Rev. Lett., 33, 1617.

Lynds, C.R., Worden, S.P., and Harvey, J.W. 1976, Ap. J., 207, 174.

McCarthy, D.W., Low, F.J., and Howell, R. 1977, Ap. J. (Letters), 214, L85.

Merrill, K.M. and Stein, W.A. 1976, Publ. Astron. Soc. Pac., 88, 285.

Nather, R.E. and Wild, P.A.T. 1973, Astron. J., 78, 628.

Neugebauer, G., Becklin, E.E., Clough, G., and Toombs, R.I. 1972, Carnegie Inst. Year Book 71, Ann. Rep. Dir. Hale Obs., 668.

Snyder, L.E. and Buhl, D. 1975, Ap. J., 197, 329.

Spears, D.L. 1977, Infrared Phys., 17, 5.

Sutton, E.C., Betz, A.L., Townes, C.H., and Spears, D.L.
    1976, Bull. Am. Astron. Soc., 8, 525.

Van Blerkom, D. and Auer, L. 1976, Ap. J., 204, 775.

Woolf, N.J. and Ney, E.P. 1969, Ap. J. (Letters), 155, L181.

Zappala, R.R. 1977, private communication.