INTERFEROMETRIC MEASUREMENTS OF FLATTENED CIRCUMSTELLAR ENVELOPES

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ABSTRACT

An incoherent spatial interferometer has been used to measure the shapes of circumstellar dust envelopes at infrared wavelengths. The objects IRC +10216, VY CMa, and NML Cyg exhibit a large variation of fringe visibility with position angle. Their circumstellar envelopes are probably flattened disks. For IRC +10216, visibility measurements from 5.0 to 20μm are discussed in detail to illustrate the physical information available from interferometric work. In VY CMa and NML Cyg, disk orientation is strongly correlated with polarimetric position angles and with the distribution of OH maser sources. Interferometric measurements are shown to be relevant to studies of star/planet formation and to studies of mass loss in long-period variables

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1 INTRODUCTION

From infrared observations of circumstellar envelopes, we seek to understand the processes of star formation, stellar mass loss, and dust formation as well as the physical and chemical properties of dust particles. Unfortunately, these goals remain unfulfilled, partly because theoretical models have had to rely very heavily on measurements of spectral energy distributions. Such models are not unique.[1] A larger variety of observations is needed. Interferometric measurements in the infrared can provide significant contributions as shown by recent theoretical studies.[2,3] Such measurements, made at different wavelengths, can probe to different levels of temperature and density in the envelope. Measurements at different position angles study an envelope's shape. Thus it is possible to map the internal structure of circumstellar envelopes.

Another hindrance to our understanding of circumstellar physics may well be the usual assumption of spherical symmetry. Although this assumption has obvious advantages theoretically, a wealth of observational evidence now argues against it in both young and old objects.[4-9] Surprisingly, very few quantitative measurements have been published concerning circumstellar shapes--even for those luminous infrared sources associated with large nebulae like VY Canis Majoris and IRC +10216. This paper presents the first interferometric measurements of circumstellar shapes and shows that flattened dust envelopes exist in three well-known infrared stars: IRC +10216, VY Canis Majoris, and NML Cygnus. Interesting correlations appear between the envelope orientations, the polarimetric position angles, the distribution of hydroxyl (OH) maser sources, and the direction of the galactic magnetic field in certain of these objects. It seems possible that disk-like structures may be the rule rather than the exception in many infrared sources.

2 TECHNIQUE

The shape measurements presented here were made with an incoherent interferometer[10] described earlier in this symposium by Dr. Low. This instrument was used at the Cassegrain focus of the Steward Observatory

90-inch telescope where it can be rotated about the optical axis to obtain fringe visibility measurements at different position angles. A 1.9m baseline was used giving a fringe spacing of 0.54 arcsec at a wavelength of 5μm.

3. IRC +10216

IRC +10216 is a late-type carbon star and long-period variable surrounded by a dense circumstellar envelope of dust and molecules This envelope extends outward to a radius of at least 1.2 arcminutes.[11,12] The high luminosity of this object ($\sim 10^4$ $L_\odot$) and its near distance of 220 pc[13] in combination with a ∿650K color temperature[14] make it the brightest 5μm source outside the solar system. It is a prime target for studies of circumstellar envelopes.

3.1 The Visibility Curve

Before presenting the shape measurements, I want to discuss the visibility curve for this object because it illustrates the type of physical information available from interferometric measurements.

Figure 1 shows fringe visibility measurements versus spatial frequency for two position angles. Note, first, that IRC +10216 is well resolved at all six wavelengths. Its shape is distinctly non-circular since the zero-points of visibility occur at different spatial frequencies. Second, the intensity distribution is very non-uniform especially in the east-west direction. This aspect can be seen by comparing observations with the dotted lines which illustrate the visibility curve of a uniform circular source having the appropriate zero-point. Possibly, the intensity distributions in the two position angles are different. Third, the visibility decreases with wavelength. Thus the angular diameter increases as we probe colder levels in the circumstellar envelope. Fourth, the north-south visibility at 5μm is virtually zero at the highest resolution. Consequently, ≤ 1 percent of the 5μm flux can come from an unresolved central star. If the stellar photosphere has an angular diameter of 0.13 arcsec[15] and a temperature of 1250K,[16] then the absorption optical depth at 5μm must be at least 4.6

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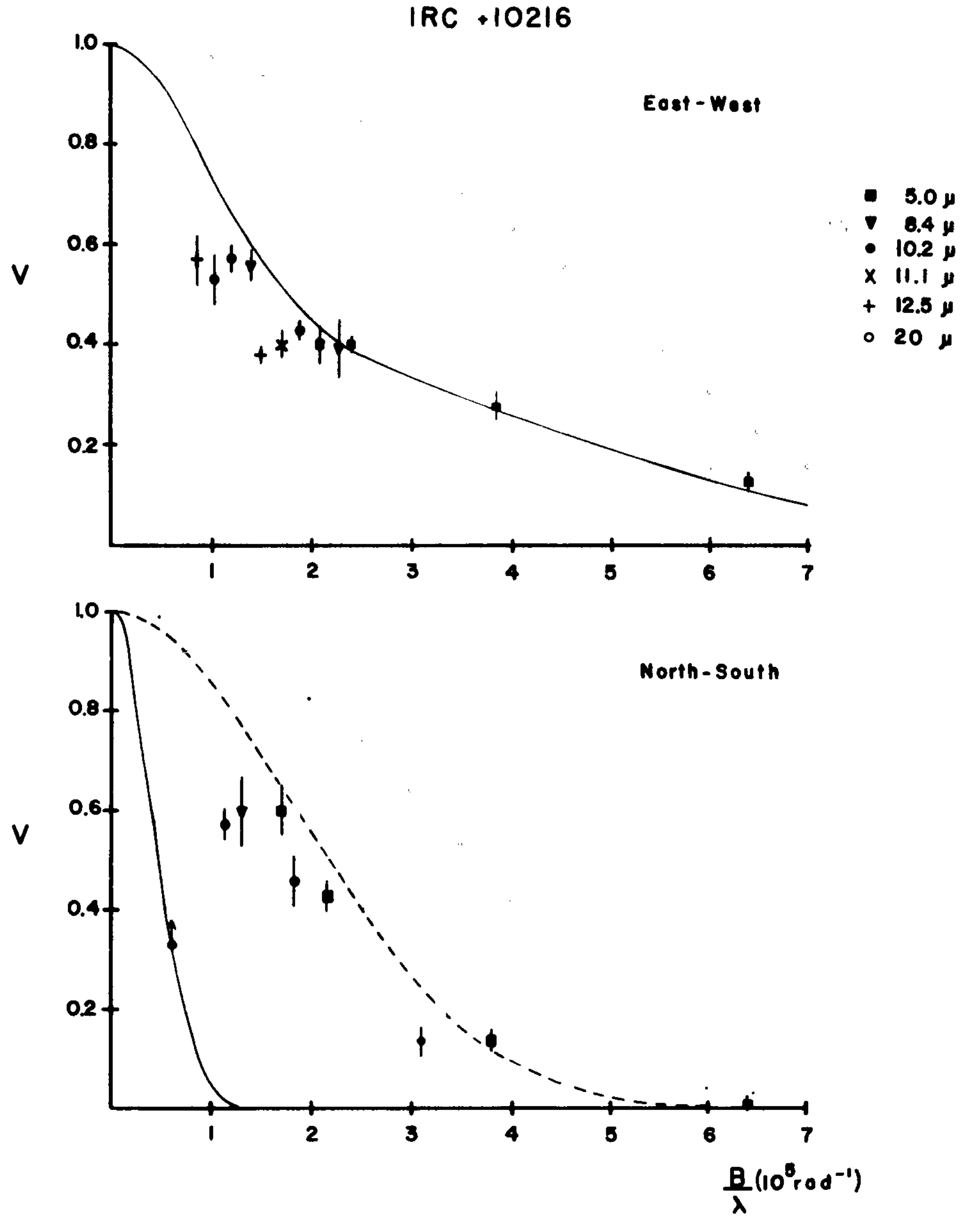

Figure 1 Fringe visibility versus spatial frequency for IRC +10216.

The figure illustrates the very extensive nature of the circumstellar envelope. In the east-west direction the 5μm emission extends radially outward from ∿0.13 arcsec (29 AU; 1.9 R_*) to $\geq$ 1 arcsec (220 AU; 15 R_*). Size increases with wavelength indicating a continuous radial distribution of flux. A density distribution proportional to r^{-2} probably exists through this region and out to $\geq$ 1.2 arcmin as indicated by radio studies of the CO molecular cloud.[11,17]

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These measurements are not consistent with the conventional model derived from lunar occultations[18] However, that model is a reasonable first approximation to the actual intensity distribution Unfortunately, it has been interpreted too literally by other investigators[19] This new interferometric data should allow a much better theoretical model to be constructed.

3.2 The Circumstellar Shape

Figure 2 displays fringe visibility measurements at 5μm for six different position angles of a 1 9m baseline. Reciprocal visibility is plotted as a vector to indicate the size of IRC +10216 as a function of position angle. Clearly the infrared shape is not circular; in fact there is a factor ∿2 difference in the visibilities north-south and east-west Also shown are the 1σ range in average position angle of linear polarization in the wavelength range 0.65-12.6μm[20-22] and the orientation of the elongated photographic image.[14] The short optical axis is along the polarization angle as expected for a disk-shaped nebula where starlight escapes perpendicular to

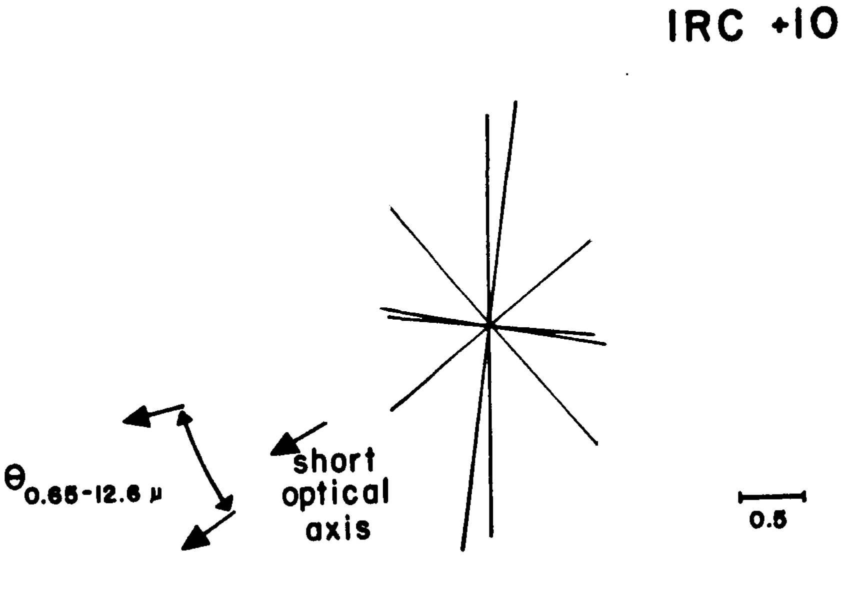

Figure 2. Shape of IRC +10216 at 5μm Measurements are represented by separate lines whose length is inversely proportional to fringe visibility and whose angle gives the position angle of observation North is up and east is left. Also shown are the 1σ range in average polarization position angle from 0.65-12.6μm and the approximate orientation of the oblong photographic image.

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the disk and is scattered by ∿90° to an observer However, the infrared elongation is inclined ∿30° to this direction The reason for this effect is not clear and requires further polarimetric and photographic study For example, although the polarization angle is generally considered constant (∿113°) with wavelength, it seems to rotate smoothly from 133° at 0.65μm to 93° at 12.6μm. Possibly the disk is slightly inclined to our line of sight.

The observed flattening and high optical depth in the infrared indicate that IRC +10216 contains a disk-like structure viewed nearly edge-on The disk is apparently oriented in the east-west direction where the interferometry shows a considerable angular range in emission at 5μm. The measured shape is elongated perpendicular to the disk because the innermost (hottest) parts of the disk are heavily obscured and/or because the dust temperature gradient is much steeper in thick disk. An identical effect is observed at 12.5μm in a similar object--the bipolar reflection nebula CRL 2688.[23]

IRC +10216 is probably the first long-period variable known to have a flattened circumstellar envelope. A disk geometry suggests that the mass loss may be caused by non-radial oscillations in the star as has been proposed to account for light variations in Mira itself[24] The flattened shape also supports an evolutionary sequence[25] in which Mira variables evolve into carbon-rich objects like IRC +10216 and CRL 2688 and later become planetary nebulae

4. VY CANIS MAJORIS

VY CMa is an M3-5 supergiant star and irregular variable embedded in a small (∿8 x 12 arcsec) nebula It is a well-known infrared source exhibiting a complex structure of SiO, H_2O, and OH maser activity Herbig[6,26] has argued that VY CMa is a very young star surrounded by a disk-shaped circumstellar envelope or "solar nebula" Recent radio studies of a bright-rimmed CO cloud near VY CMa show the star to be massive (∿15 $M_\odot$) and luminous (5 x 10^5 $L_\odot$) and confirm its association with a region of star formation[27] However, the proposed disk geometry has never been confirmed by direct measurements.

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Figure 3 shows our visibility measurements versus position angle for VY CMa at 10.2μm. As before, reciprocal visibility is plotted as a vector. Clearly the shape is not circular. The short dimension lies along the position angle of linear polarization at 0.55μm[20] and also along the elongated distribution of OH maser sources seen in a high resolution map at 1612 MHz.[28] The polarization angle decreases with increasing wavelength becoming roughly orthogonal to the optical value between 1.2-10μm,[29,30] where it is aligned with the long dimension of the 10.2μm emission.

The rotation of polarization angle with wavelength is well-known. Serkowski[31] proposed an explanation based on Herbig's model of a flattened circumstellar disk inclined to our line of sight. To be consistent with the observed polarimetry, this explanation requires that the disk runs parallel to the optical polarization angle and therefore orthogonal to the

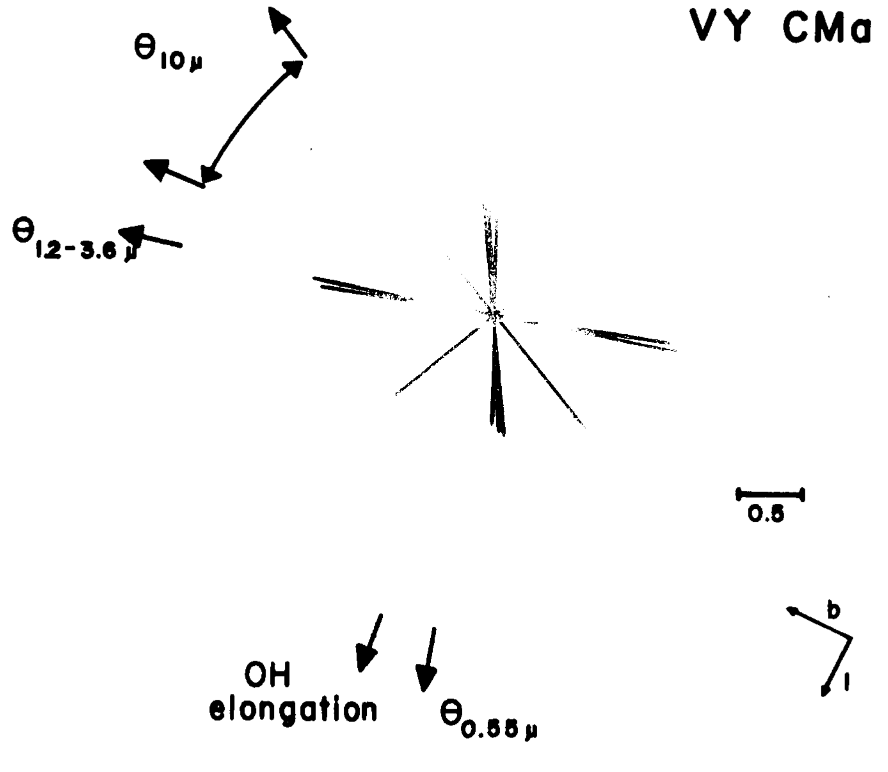

Figure 3 Shape of VY CMa at 10.2μm. Reciprocal visibility is plotted versus position angle. North is up and east is left. Also shown are the measured polarization position angles at several wavelengths and the direction of elongation of OH maser sources. Directions of galactic longitude (l) and latitude (b) are indicated. The galactic magnetic field is roughly parallel to the OH elongation.

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measured elongation at 10.2μm. This effect was also inferred for IRC +10216 and is probably caused by a radial temperature gradient in the dust envelope which is steeper in the disk plane than along the polar axis.

Figure 4 shows Herbig's map[32] of the optical nebula. Contour lines depict flux levels of unpolarized radiation. Line segments show the spatial variation of the magnetic vector of linear polarization at 0.65μm. The radially symmetric pattern is characteristic of reflection by dust. The amount of polarization reaches 70 percent in one region but is much smaller elsewhere. This variation of polarization is consistent with the presence

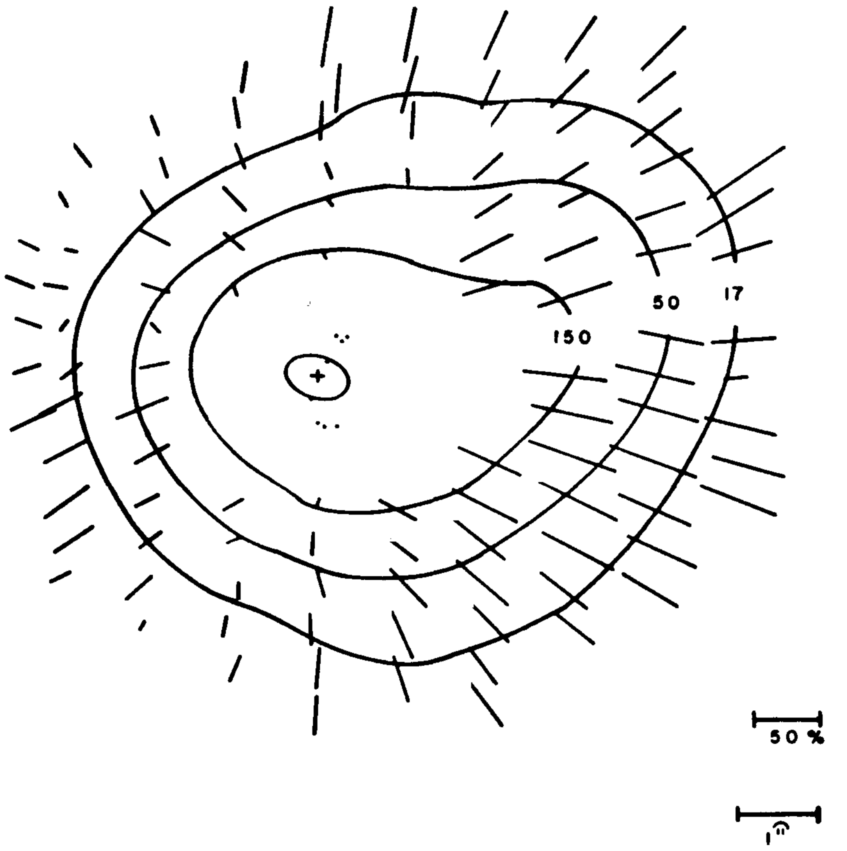

Figure 4. Characteristics of the VY CMa nebula. Superimposed on Herbig's map of the optical nebula are the interferometric results at 10.2μm (inner oval) and the positions of OH maser sources (dots). North is up and east is left. Three outer contours connect points of equal unpolarized flux in arbitrary units. Line segments denote the spatial variation of the magnetic vector of linear polarization at 0.65μm. Scales of percentage polarization and spatial resolution are at lower right. A cross marks the direction to the star.

of a flattened circumstellar disk whose leading edge is inclined toward the direction of lowest polarization. An inner oval shows our measurements at 10.2μm; this emission is assumed to be centered on the star A Gaussian fit to the visibility data gives an angular size at e^{-1} intensity points of 0.50 x 0.73 arcsec. The infrared image is elongated along the polar axis of the inferred disk.

Dots in Figure 4 are positions of the main spectral features in OH maser emission at 1612 MHz.[28] The feature at 4.6 Km/sec has a very small angular size (<0.02 arcsec) and is assumed to indicate the direction to the central star These sources are located in a region roughly 2.5 arcsec in size which is elongated along the circumstellar disk we have been discussing. These facts strongly suggest that the OH maser activity is generated in the disk plane predominantly outside the area of 10.2μm emission Unfortunately, other OH maser maps at lower spatial resolutions do not show such a nice correlation with the inferred disk; elongated distributions are still observed but at a position angle of ∿210° instead of ∿160° [33] It is important to add that a disk-like geometry has also been proposed from line-profile studies of the SiO and H_2O maser emissions [9,34]

Magnetic fields are thought to influence the formation of stars so it is of interest to ask how the galactic magnetic field is oriented relative to the flattened disk in VY CMa. Mouschovias[35] has predicted that a collapsing interstellar cloud will flatten with its long dimension nearly aligned with the magnetic field. Measurements of interstellar polarization[36] in the region of VY CMa suggest that the field direction runs parallel to the disk.

Although many of these arguments are somewhat qualitative, it seems certain that VY CMa is a very young star embedded in a flattened circumstellar disk. Therefore, we have an opportunity to examine the physical processes leading to the formation of planets.

5. NML CYGNUS

NML Cyg is an M-type star whose energy distribution, polarization characteristics, and maser activity are very similar to those of VY CMa.

However, there are important differences in the spectra, variability, and sizes of these objects.[37] Interferometric measurements in the infrared reveal further differences.

Figure 5 shows our visibility measurements at 5µm. Clearly, the shape is not circular. The visibilities are high, indicating a small size of ∿0.15 x 0.22 arcsec, based on a Gaussian brightness distribution. As in VY CMa, the polarization angle rotates ∿90° from the blue into the infrared and suggests a disk structure inclined to our line of sight. However, the polarimetry of NML Cyg shows exactly the opposite correlation with measured shape. The long dimension at 5µm is oriented parallel to the optical polarization angle, which as before is parallel to an oblong distribution (∿2.5 x 3.5 arcsec) of OH maser sources.[38]

In contrast to VY CMa, the image of NML Cyg is stellar with an angular diameter ≤0.7 arcsec at 0.8µm.[39] No significant nebulosity is seen around NML Cyg even though it is at least three times closer to us. Other

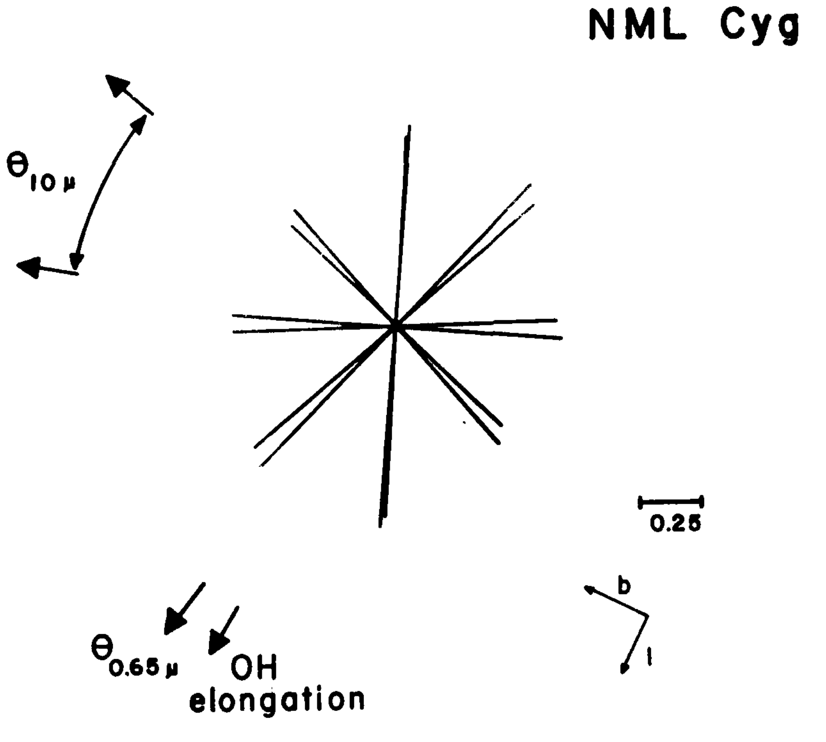

Figure 5. Shape of NML Cyg at 5µm. Reciprocal visibility is plotted versus position angle. North is up and east is left. Also shown are the measured polarization position angles at several wavelengths and the direction of elongation of OH maser sources.

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observations indicate a high optical depth in this object For example, the star is optically very faint ($m_{pg} \geq 21$) and exhibits a "silicate" absorption feature at 10μm. However, VY CMa is a brighter visual object (m_{pg} = 10.0 - 10.9) and displays a strong emission feature at 10μm. The high optical depth and lack of bright nebulosity in NML Cyg suggest that the interferometry measures directly the size of the circumstellar disk instead of the illuminated polar regions.

The observed correlation between polarization angles and shape argue strongly against a distance of ≥500pc which requires a large component of interstellar polarization [40] A distance of 200pc and a classification of M6III is more likely.[41] At this distance the galactic magnetic field appears inclined to the circumstellar disk by ∿45° which might argue for an evolved object. In addition NML Cyg is not associated with a region of star formation.

6. CONCLUSIONS

Table 1 summarizes the shape measurements of IRC +10216, VY CMa, and NML Cyg. It appears that axi-symmetric circumstellar envelopes may be commonplace among both young and old objects With interferometric techniques we can study the formation of planets as well as the later phases of stellar evolution Correlations between disk orientation, polarization angle, and the distribution of maser sources may help answer unsolved problems concerning the origin of polarized radiation and maser activity in such objects Disk orientation may have important effects on the observed spectral energy distribution.

TABLE 1

SHAPE MEASUREMENTS

Object	D(pc)	λ (μm)	Angular Size (arcsec)	Linear Size (A.U.)
IRC+10216	220	5.0	(0.25 x 0.50)→ ≥ 2	(55 x 110)→ ≥ 450
VY CMa	1500	10.2	0.50 x 0.73	750 x 1100
NML Cyg	200	5.0	0.15 x 0.22	30 x 44

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DISCUSSION

N.W. Boggess: What is the percentage polarization in IRC + 10216?

D.W. McCarthy Jr.: A maximum of ∿ 20% is observed at 1μm at minimum phase in the ∿ 650 day light cycle.

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