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10 μm SPECKLE INTERFEROMETRY OBSERVATIONS OF EVOLVED STARS

J. A. Benson, N. H. Turner,[a] and H. M. Dyck
Wyoming Infrared Observatory, University of Wyoming, Laramie, Wyoming 82071
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ABSTRACT

We present 10 μm spatial visibility data for 17 late-type stars. We have multiple observations for most of the stars and find that a majority of their surrounding circumstellar dust shells are at least partially resolved with a 2.3 m telescope. We fit single and two-component Gaussians to our visibility data and briefly compare our results with the models of Rowan-Robinson and Harris.

I. INTRODUCTION

Evolved stars are some of the brightest infrared sources in the sky. Early studies of cool stars showed that their often large IR excesses could be attributed to surrounding circumstellar dust (Gillett *et al.* 1971). Typical models of the dust shells (e.g., Rowan-Robinson and Harris 1982, 1983a,b, hereafter referred to as RR&H) predict dust temperatures in the range 500–1000 K. The Planck curve for dust at these temperatures peaks near the 10 μm window; hence 10 μm is a good wavelength choice for studying the actual distribution of the dust. The observation of angular diameters of circumstellar shells provides an important additional constraint for the models of these objects, although few angular-diameter measurements exist at 10 μm (e.g., Howell, McCarthy, and Low 1981; Townes and Vanderwyck 1984; Fix and Cobb 1988). The predicted shell size from the models of RR&H range from 0.002 to 1.1 arcsec. Clearly, the study of objects in this angular-size range requires interferometric techniques at infrared wavelengths.

The 2.3 m Wyoming Infrared Observatory (WIRO) telescope has a diffraction limit at 10 μm of about 0.9 arcsec. Our past experience using speckle-interferometry techniques has shown that we can reach this limit at WIRO. Further, we can measure partially resolved sources a factor of 5 or so below this limit. Our speckle-interferometry limits are therefore very close to the expected shell diameters. Thus, we were strongly motivated to survey a group of candidate evolved stars for shell angular diameters. In the rest of this paper we report the results of that survey.

II. THE OBSERVATIONS

We have developed a standard infrared one-dimensional (1*D*) speckle-interferometry system at WIRO. Currently, we are using a conventional helium-cooled bolometer equipped with a 275-μm-wide slit. The observations reported here were all made with an *N* band filter centered at 10 μm with a bandpass of 5.8 μm.

Our observation scheme consists of the traditional technique of using the secondary mirror to scan the image across a slit placed in front of the detector, in a time short compared to the atmospheric-stability time. For typical seeing conditions at 10 μm, this requires a scan rate of approximately 2 Hz. An observation sequence consists of alternating between a point source and the object of interest, interleaving each measurement with scans of the nearby sky. Typically 256 scans are obtained at each location. Each scan is Fourier transformed and the power spectra are coadded in real time. Subtraction of the noise scans and ratioing the object to the point source removes the atmosphere–telescope transfer function, yielding the square of the object visibility. This cycle is repeated until the desired S/N is obtained.

[a] Wyoming Infrared Observatory Summer Undergraduate Research Assistant, supported by NSF Research Experience for Undergraduates Program grant no. AST87-12280.

III. RESULTS

The data that are reported here were obtained during the period 1987 June–August. We find that all the visibility data can be fit very nicely with single or, in some cases, the sum of two Gaussians. As previously noted by Ridgway *et al.* (1986), this simple functional fit is appropriate for the interpretation of 1*D* speckle data. The intrinsic one-dimensional integrating behavior of a long narrow slit tends to smooth out the actual radial-intensity distribution for an azimuthally symmetric source. Hence 1*D*, single wavelength, speckle data are not directly useful for determining the radial-intensity distribution of a shell. One can, however, compare the size as determined from Gaussian fits to detailed model calculations (e.g., RR&H), provided the Gaussians are properly scaled. Ridgway *et al.* (1986) give a convenient table from which the scaling factors for a variety of model parameters can be obtained.

In Fig. 1 we have shown examples of fits to visibility data

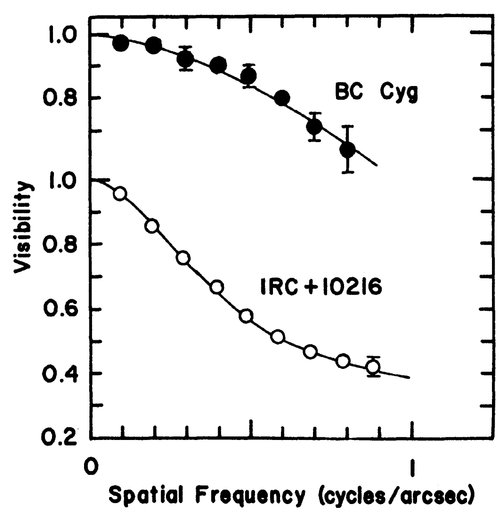

FIG. 1. Example of 10 μm visibility data for two stars from our survey. The observations are shown as points with 1σ error bars (when the error exceeds the size of the plotted point). The solid curves are simple models fitted to the observations.

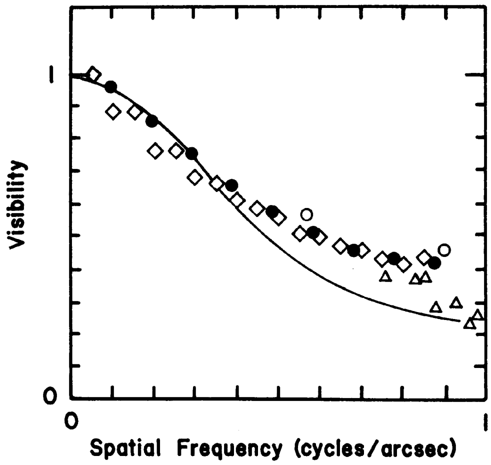

FIG. 2. Comparison of various observational data for IRC + 10216. The dark circles (●) are from this paper; the light circles (○) are from McCarthy *et al.* (1980); the light triangles (△) are from Sutton *et al.* (1979); and the light diamonds (◇) are from Dyck *et al.* (1987). These are all interferometric measurements. The solid line is a simulated visibility from Bloemhof *et al.* (1988) taken using noninterferometric techniques.

for BC Cyg, an M supergiant, and IRC + 10216, the archetypal peculiar carbon star. For BC Cyg a single-component Gaussian curve is sufficient to fit the data. Formally, we obtain a full width at half maximum intensity (FWHM) $\theta = 0.41 \pm 0.05$ arcsec. For objects like BC Cyg, which do not show evidence of the underlying star, the scale size obtained from the fit is a lower limit.* The existence of a more compact component will tend to raise the visibility curve, which in the absence of higher-spatial-frequency information, can only be interpreted as a less resolved object.

For IRC + 10216 a simple Gaussian will not fit the data. In Fig. 1 we have fitted a two-component core–halo model to our data. The FWHM of the halo is $\theta = 1.5$ arcsec, while that of the core is $\theta = 0.32$ arcsec. In Fig. 2 we have shown a compilation of interferometric data for IRC + 10216 from various sources. The agreement among the sets is generally good. However, the addition of the Michelson interferometry by Sutton *et al.* (1979) indicates that the visibilities begin to decrease more rapidly, at about 0.8 cycles/arcsec, than our simple core–halo model predicts. The decreasing trend continues in the Sutton *et al.* data to even higher spatial frequencies. This requires that the core component be slightly more resolved than we inferred from our data alone.

Only IRC + 10216 and α Ori require two-component fits. In the case of α Ori the more compact component was completely unresolved. Howell *et al.* (1981) also fit their 1.6 μm α Ori visibility data with two-component models, consisting of a resolved and unresolved component. They found that their data could be fit equally well by a uniform disk of diameter 4.0 ± 0.5 arcsec or by a Gaussian of diameter 3.4 ± 0.5 arcsec at the $1/e$ points. For both models their unresolved component contribution was 58%. Our recent N band data on α Ori is consistent with a Gaussian of diameter

*For these objects, our observations do not extend to sufficiently high spatial frequencies to show the characteristic flattening of the visibility curve produced by an additional compact component.

TABLE I. 10 μm speckle-interferometry observations made at WIRO during 1987.

Name	Nature[a]	PA(°)	Θ_NFWHM(″)	Θinner(″)	Θ_N/Θinner	(N)[b]
RX Boo	Par Res	0	0.29	0.13 - 0.50	0.9	4
R Cas	Par Res	0	0.33	0.07 - 0.14	3.1	2
T Cas	Par Res	0	0.26	0.06 - 0.11	3.0	2
U Cep	Par Res	0	0.37	0.19	1.9	1
Cit 6	Par Res	0	0.33	0.02 - 0.13	4.3	2
S Crb	Par Res	0	0.24		—	1
BC Cyg	Par Res	0	0.41	0.32	1.2	2
BI Cyg	Par Res	0	0.35	0.28	1.2	3
NML Cyg	Par Res	0	0.36	0.08	4.5	4
χ Cyg	Par Res	0	0.27	0.08 - 0.20	1.9	4
MW Her	Unres	0	—	0.02 - 0.15	—	2
U Her	Par Res	0	0.26	0.17 - 0.32	1.0	1
X Her	Par Res	0	0.22		—	2
IRC+10216	Core-Halo	0	1.5 (56%)	0.36	4.3	1
α Ori	Core-Halo	0	2.7 (62%)	0.51	5.3	2
S Per	Par Res	0	0.30	0.03	10.0	1
SW Vir	Par Res	0	0.28		—	1

[a] Par Res = partially resolved; Unres = unresolved;

Θ_NFWHM = full width at half maximum of Gaussian fit to visibility data at $\lambda = 10.0$ μm; uncertainties are typically $\pm$ 0.05″. For the core-halo models, the FWHM of the larger component only and the fraction of the total flux (in parentheses) contributed by the compact component is given.

Θinner = predicted shell size from Rowan-Robinson and Harris (1983); where a range is given, the range is for the extremes of the light curve.

Θ_N/Θinner = measured full width at half maximum divided by the mean shell diameter as given by RR&H.

[b] N = the number of independent measures of the source.

3.2 ± 0.1 arcsec at the $1/e$ points (2.7 ± 0.1 arcsec FWHM). The unresolved component contributes approximately 62% of the total flux.

In Table I we list the FWHM (in object space) of the Gaussian fits to our visibility data for all 17 stars. For IRC + 10216 and α Ori we show intensity ratio of the compact, or unresolved, component to the total flux. In addition, for ease of comparison with the stars that RR&H modeled, we show their predicted inner-shell diameter.

We note that, of the 17 stars surveyed, only one—MW Her—was found to be completely unresolved. Two objects (IRC + 10216 and α Ori) have some fully resolved structure, and the remaining stars show partially resolved circumstellar shells. This high percentage of success indicates that a 2 m class telescope can make substantial contributions to the study of shell structures.

One final point is shown in Fig. 2: Bloemhof *et al.* (1988) have obtained drift-scan image profiles of IRC + 10216 using a linear detector array. In their paper, Bloemhof *et al.* present a simulated visibility curve obtained by assuming that the geometry of the source is centrosymmetric. We have shown their simulated visibility in Fig. 2 as a solid line. There is general agreement between the interferometry and simulated visibility data at low spatial frequencies (< 0.4 cycles/arcsec) and again near 1 cycle/arcsec. At intermediate frequencies (0.4–0.9 cycles/arcsec), corresponding to spatial scales 1.1–2.5 arcsec, there is disagreement, amounting to as much as 25% of the interferometrically measured visibility. This difference could result from intrinsic variations in the source shell structure. However, our recent measurements and those of Dyck *et al.* (1987) bracket the Bloemhof *et al.* data in time and, further, agree with one another at the spatial frequencies in question. Thus, we are inclined to rule out secular variations, although pathological changes could reproduce the effect. Alternatively, the difference could arise from (i) the assumptions leading to the symmetric simulated visibility, (ii) some systematic difference in observation technique, or (iii) different scan directions. At this point it is not possible to judge.

IV. CONCLUSIONS

We have directly measured the angular size at 10 μm of a number of circumstellar dust shells around evolved stars. We find that our measurements of the FWHM of the shells are typically 0.9–5.3 times larger than the predicted inner-shell diameters based on detailed spectrophotometry and model fitting as performed by RR&H. For typical shell parameters at 10 μm, the scale factors from the Ridgway *et al.* (1986) paper show that a Gaussian fit to a spherical shell should yield a FWHM that is between 2 and 10 times larger than the inner-shell diameter. The exact factor depends on inner-shell temperature, radial-temperature dependence, and opacity. Given the uncertainties in these quantities, we find that our direct measures of the shell sizes are generally in very good agreement with the predictions of RR&H.

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