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Large amplitude periodic variations in the angular diameter of R Leonis

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ABSTRACT
We report the first direct detection of long-term periodic diameter variations in a Mira variable. Angular diameter measurements of the 313 d period variable R Leonis at 833 nm and 940 nm obtained between 1996 February and 1997 June using the Cambridge Optical Aperture Synthesis Telescope (COAST) and the William Herschel Telescope (WHT) show a cyclic modulation of the apparent stellar diameter by approximately 35 per-cent. The agreement between these new data and archival measurements from 1992 January suggest coherence in the modulation over a 5 year period. Our data are consistent with recent models which suggest that, in photometric bands with only weak to moderate molecular contamination, periodic variations in stellar diameter of order 50 per-cent can be maintained. The measurements indicate that the apparent stellar diameter was largest at visual phase 0.5 and that any phase shifts between the visual light-curve and those at 833 nm and 940 nm were at most 0.05. The large offset (~ 0.25) between the phase of the observed diameter maximum and that predicted for the photospheric continuum diameter variations suggests that our observations are more sensitive to the changing temperature structure of the outer atmosphere than to the deeper continuum-forming layers.

Key words: techniques: interferometric – telescopes – stars: imaging – stars: AGB and post-AGB – stars: individual: R Leo – stars: variables: other.

1 INTRODUCTION

Despite considerable effort, the detailed understanding of the observable properties of long-period variable stars (LPVs) still presents considerable difficulties. The need to accommodate pulsation, radiation transport, and molecule and grain formation simultaneously in models has meant that most studies have concentrated on either the dynamics of the pulsation (see, e.g. Ya'ari & Tuchman, and references therein) or the properties of the spectrum at a given instant (e.g. Fox & Wood 1985; Scholz & Takeda 1987; Bessell et al. 1989; Gillet, Lafon & David 1989).

In a new initiative, Bessell and co-workers (Bessell, Scholz & Wood 1996, BSW) have begun to investigate the phase and cycle dependence of the observable properties of Mira variables. Their models provide, not only the stellar luminosity, but also the spectrum, colours, monochromatic radii, and absorption line profiles as a function of time. However, whilst monitoring of the light-curves, colours and line properties of Mira variables is not uncommon (see, e.g. Celis 1986; Barnbaum & Hinkle 1995; de Laverney et al. 1997) there have been few studies of the temporal changes in the apparent angular sizes of LPVs. The use of this observable as a diagnostic for theoretical time-varying models has thus been largely unexplored.

Recently, a number of groups have been pursuing the use of interferometric methods to monitor the diameters of LPVs. Van Belle et al. (1996) used the IOTA interferometer to obtain a sample of predominantly single-epoch $2.2\,\mu$m diameter measurements of 18 oxygen-rich Miras and investigated the effective temperature and radius of a "generic" LPV as a function of variability phase. The only specific campaign to search for periodic size variations in an individual LPV, though, has been that of Tuthill, Haniff & Baldwin (1995). Tuthill et al. repeatedly measured the angular size of o Ceti with the William Herschel Telescope (WHT) during a two year period between 1991 September and 1993 December and, while failing to discover any regular modulation, did detect an unexpected large increase in the size of the star which they associated with the passage of an aperiodic shock through the stellar atmosphere.

With the completion of the Cambridge Optical Aperture Synthesis Telescope (COAST) we have begun a pro-

Table 1. Log of observations at COAST and the WHT. Dates refer to the start of the night of each observation. Where multiple dates are present this implies that data from a number of nights were combined to permit a reliable diameter estimate to be obtained. Note that the observations from 92/01/20 have been reported previously (Tuthill et al. 1994). The visual phases were computed from the ephemerides in the 1996 and 1997 Observer's Handbook of the Royal Astronomical Society of Canada and data from the American Association of Variable Star Observers (AAVSO) (Mattei, private communication). N_{vis} and N_{cl} refer to the number of visibility and closure-phase measurements made. An identical number were made for the calibration source. Each "measurement" corresponds to either 99 seconds (COAST) or 60 seconds (WHT) of observations. τ_c is the mean of the coherence times at the longest observed wavelength, i.e. the length of time over which the autocorrelation-function of the fringe signal fell to half its zero-delay value: this characterises the longest useful coherent integration time.

Date(s)	Telescope	Pulsation phase	Baseline range (m)	940/50 nm N_{vis}	940/50 nm N_{cl}	830/40 nm N_{vis}	830/40 nm N_{cl}	τ_c (ms)
92/01/20	WHT	0.26	0.6–3.8	-	-	36	24	-
96/02/26, 27	COAST	5.05	2.7–5.2	38	27	137	-	5.3
96/03/29, 96/04/03	COAST	5.16	2.7–4.5	44	9	49	-	5.9
96/05/03, 04, 06	COAST	5.27	2.7–5.6	31	-	6	-	6.5
97/01/24	COAST	6.11	3.0–8.3	11	-	0	-	8.6
97/02/07	COAST	6.16	3.5–4.2	16	-	5	-	4.7
97/03/30	COAST	6.32	4.0	4	-	4	-	10.8
97/04/07	COAST	6.35	2.7–6.2	24	-	9	-	8.0
97/04/14	COAST	6.37	3.4–3.8	4	-	0	-	9.4
97/04/15	COAST	6.37	3.4–4.0	2	-	3	-	8.4
97/04/17	COAST	6.38	3.4–4.4	5	-	0	-	10.7
97/04/20	COAST	6.39	1.9–3.2	4	-	2	-	9.9
97/04/21	WHT	6.39	0.3–3.7	70	70	80	80	-
97/04/23	COAST	6.40	2.8–3.1	4	-	0	-	4.5
97/04/30	COAST	6.42	3.6	2	-	1	-	7.0
97/05/12	COAST	6.46	2.5–2.7	6	-	0	-	8.5
97/05/28, 29, 30, 31	COAST	6.52	1.9–3.3	22	-	6	-	5.9
97/06/22	WHT	6.60	0.3–3.7	30	30	40	40	-

gramme monitoring the sizes of the nearest LPVs. In this paper we present measurements of the bright Mira R Leonis secured over a 2-year interval at COAST and combine these with additional measurements made at the WHT. We report the detection of a large amplitude coherent periodic variation in the apparent angular diameter of the star, visible at both 833 nm and 940 nm. We discuss this in the context of current models for LPVs and argue that future measurements made with separated-element interferometers should soon uncover similar variations.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Measurements with COAST

2.1.1 Observations

Measurements of R Leonis were made with the COAST interferometer between 1996 February 26 and 1997 May 31, a period encompassing two pulsation cycles of the star. For a brief introduction to the instrument the reader is referred to Baldwin et al. (1996) and Burns et al. (1997).

The current implementation at COAST uses four 40 cm telescopes, though for the earliest observations reported here only three of these were operational. As is usual for visible COAST observations, the beams from the telescopes were stopped down to 16 cm so as to better match the seeing at the site ($\sim 1.5''$). At each epoch, visibility amplitude measurements were made sequentially on all the baselines for which fringes could be detected. In most cases the separate output channels of the telescope were used to measure different wavelengths and so the fringes were usually acquired at 940 nm where the star was least resolved. Whenever fringes were measurable on at least two baselines sharing a common array element closure phase observations were also secured. The large apparent size and often faint visual magnitude of the star, however, meant that at most epochs this was not possible.

Observations were made in one of four bandpasses (940/50 nm, 905/50 nm, 880/50 nm, 830/40 nm), the majority being centred at 940 nm or 830 nm. Because of the better sampling of pulsation phase at these wavelengths, hereafter we shall restrict attention to these two colours alone. The measurements of R Leonis were interleaved with observations of the B7V calibration star α Leonis. This has an apparent angular diameter of 1.4 mas (Ridgway at al. 1982) and so is completely unresolved on all the baselines used for this study: these typically ranged from 2.7 m to 4.5 m on any individual night. Details of the observations are given in Table 1.

2.1.2 Data reduction

Processing of the raw data to estimate Fourier quantities was carried out using standard methods, i.e. accumulation and integration of the mean power spectra of the fringes for the visibility amplitudes, and coherent integration of the

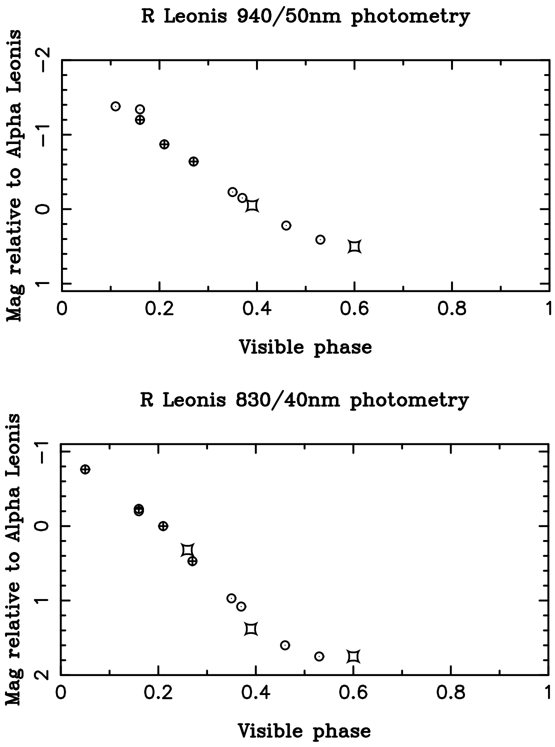

Figure 1. Relative photometry for R Leonis calibrated against α Leonis at 940 nm (top) and 830 nm (bottom). In each case the data are plotted against the phase of the visual lightcurve obtained from AAVSO records. The coding of the symbols is as follows: diamonds WHT observations, crossed circles 1996 COAST data, dotted circles 1997 COAST data. The typical errors for each point are ± 0.05 mag. As is normal for Miras, the amplitude of the light-curve decreases with increasing wavelength.

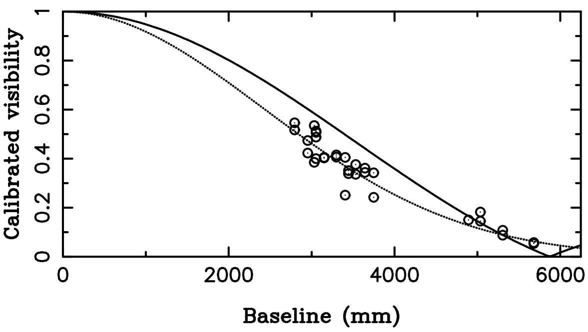

Figure 2. The 940 nm visibility function for R Leonis as measured at COAST on 96/05/03. The curves show the visibility functions of the best-fit uniform-disk (solid) and Gaussian (dotted) models. At this epoch the relative preference for a Gaussian as opposed to a disk model was at its maximum. The errors on the measured data are typically 7.5 per-cent of their value.

instantaneous triple-products for the closure phases. Further details of the procedures can be found in Burns et al. (1997).

The measured calibrator visibilities were typically in the range 0.2 to 0.4, depending mainly on the atmospheric stability and system alignment at the time of observation. After calibration, the formal errors on the source visibility amplitudes were approximately 5 per-cent of their values, though near photometric minimum these errors increase to of order 10 per-cent. As expected for an unresolved source, the calibrator star gave closure phases with a mean of $0°$, and in all cases the closure phase values were less than $10°$. The source closure phases had similarly sized errors, though when the triple-product amplitudes were at the limit of measurement they sometimes increased to as much as $\sim 20°$.

2.2 Measurements with the WHT

2.2.1 Observations

Interferometric measurements were made in 1997 April and 1997 June at the Ground-based High Resolution Imaging Laboratory (GHRIL) of the WHT using a conventional aperture synthesis imaging set-up (see, e.g. Buscher et al. (1990)). This allowed for the insertion of an aperture mask in a re-imaged pupil plane to select a number of interferometer baselines, and magnifying optics to permit sampling of the resulting fringe patterns on a fast-readout CCD. Exposure times of 12 ms were used to freeze the seeing, together with a five-hole pupil mask that gave 10 baselines in the range 0.3 m – 3.7 m.

The measurements were made using the same filter bandpasses as at COAST with α Leonis again serving as the calibration star. To sample the Fourier plane well, the aperture mask was rotated relative to the sky and five thousand short-exposure images were secured at each of up to nine separate position angles. As in previous observations, the scale and orientation of the detector were determined by observations of two close visual binary stars with well-known orbits. Details of the observations are given in Table 1.

2.2.2 Data reduction

The raw short-exposure images were analysed using standard techniques (Haniff et al. 1987; Buscher et al. 1990) to extract estimates of the visibility amplitudes and closure phases. These were then corrected for atmospheric and instrumental effects using the calibrator star data. The final errors on the calibrated data were between one and three per-cent for the visibilities and between $2°$ and $10°$ for the closure phases.

2.3 Photometry

Because of the frequent calibrations required, it was possible for photometry of R Leonis relative to α Leonis to be derived for most of the times when interferometric observations were made. The photometric fields of view, i.e. the angles on the sky over which flux would be detected, at COAST and the WHT were approximately $20''$ and $3''$ and thus comfortably large enough to accept a seeing-limited image yet sufficently small to limit the effects of any sky/lunar background.

α Leonis has been used as both a $uvby\beta$ (Perry et al. 1987) and JHK (Carrasco et al. 1991) photometric standard star, and so we have assumed that its flux in our bandpasses remained constant between 1992 and 1997. After normalizing relative to α Leonis, the errors on the photometry, based on the scatter of repeated measurements, were in the range

Table 2. Uniform-disk diameter of R Leonis measured at 940 nm and 830 nm. Note the generally good agreement betwen contemporaneous measurements at COAST and the WHT. The WHT measurement from 92/01/20 is that of Tuthill et al. (1994) obtained using essentially identical methods and equipment to that described here.

Date	Pulsation phase	Telescope	Angular diameter (mas) 940/50 nm	830/40 nm
92/01/20	0.26	WHT	-	44.9 ± 2.0
96/02/26	5.05	COAST	36.3 ± 1.3	37.7 ± 1.3
96/03/29	5.16	COAST	37.8 ± 1.0	41.0 ± 1.5
96/05/03	5.27	COAST	40.3 ± 0.7	48.6 ± 1.5
97/01/24	6.11	COAST	38.0 ± 2.0	-
97/02/07	6.16	COAST	39.8 ± 4.0	41.8 ± 2.0
97/03/30	6.32	COAST	44.5 ± 0.1	42.8 ± 0.1
97/04/07	6.35	COAST	43.4 ± 3.9	47.7 ± 3.5
97/04/14	6.37	COAST	43.2 ± 1.8	-
97/04/15	6.37	COAST	43.5 ± 1.3	45.2 ± 1.0
97/04/17	6.38	COAST	44.4 ± 2.3	-
97/04/20	6.39	COAST	47.5 ± 2.0	52.5 ± 2.0
97/04/21	6.39	WHT	46.9 ± 3.3	47.8 ± 2.0
97/04/23	6.40	COAST	48.2 ± 2.5	-
97/04/30	6.43	COAST	41.2 ± 2.0	45.4 ± 2.0
97/05/12	6.46	COAST	51.2 ± 3.4	-
97/05/28	6.53	COAST	51.5 ± 3.0	49.0 ± 5.5
97/06/22	6.60	WHT	50.2 ± 2.8	50.8 ± 1.6

0.01 – 0.11, with a median of 0.05 magnitudes. The folded 940/50 nm and 830/40 nm lightcurves for R Leonis are shown in Fig. 1.

3 RESULTS AND DISCUSSION

3.1 Angular Sizes

Following Tuthill et al. (1995) we have estimated the stellar “size” by fitting circularly symmetric models — either uniform disks or Gaussians — to the visibility data. In view of previous indications of non-spherical structure in certain Mira variables (Karovska et al. 1991; Quirrenbach et al. 1992; Haniff et al. 1992), prior to model-fitting the visibility amplitudes and closure phases were examined for evidence of elliptical or asymmetric structure. In all cases no significant signature of ellipticity was found. In 1996 February the closure phases measured at COAST did indicate evidence for unresolved surface structure on the star. However, the best estimate for the maximum flux associated with such a feature was only three per-cent of the total. Data from the WHT in 1997 April similarly showed clear evidence for small scale structure at a level of a few percent of the total flux, but in neither case is it likely that the presence of any “hotspots” will have biased our size estimates significantly.

The problems associated with both defining and interpreting stellar radii in Mira variables are well known (see, e.g. the discussions in Scholz & Takeda 1987 and Bascheck, Scholz & Wehrse 1991) and so the adoption of simple one-parameter models to describe the stellar brightness distribution, as we have chosen here, makes interpretation of the stellar sizes in terms of given physical layers in the atmosphere difficult. Nevertheless, as quantitative measures of the emitting regions, and for the purposes of identifying any periodic trends the use of such models should be adequate.

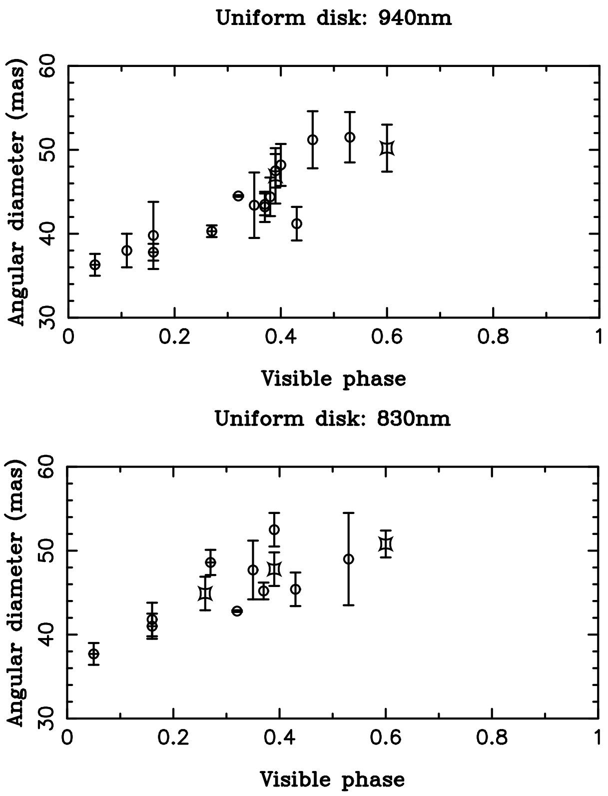

Figure 3. Uniform-disk angular diameters and 1σ error estimates for R Leonis at 940 nm (top) and 830 nm (bottom). In each case the data are plotted against the phase of the visual lightcurve obtained from AAVSO records. The coding of the symbols is as follows: diamonds WHT observations, crossed circles 1996 COAST data, dotted circles 1997 COAST data. Note that the WHT datum at phase 0.26 is the 830 nm measurement of Tuthill at al. (1994) from 1992. Conversion to Gaussian FWHM can be performed, if necessary, using the values of R, the ratio of the Gaussian FWHM to the uniform-disk diameter, quoted in the main text. At the HIPPARCOS distance of the star, an angular diameter of 40 mas corresponds to a physical radius of 436 $R_{\odot}$.

In general, Gaussian functions provided much better fits to the data (see Fig. 2), particularly when the visibility functions dropped below 30 per-cent, as was often the case with the COAST data. This confirms the finding of Haniff et al. (1995) who reported that in an interferometric survey of 10 Mira variables, their visibility functions were better fit by Gaussian rather than uniform disk profiles. Nevertheless, the ratios, R, of the fitted Gaussian FWHM to the uniform disk diameter were remarkably constant — at 940 nm R was 1.52 ± 0.04 and at 830 nm $R = 1.48 \pm 0.17$ — indicating that either model could be usefully used to characterize the stellar size.

The measured uniform-disk diameters of R Leonis obtained using these procedures are given in Table 2 and displayed graphically in Fig. 3. The most significant feature of Fig. 3, which shows the angular diameter measurements folded to the visual lightcurve phase, is the large phase-coherent modulation. This is present at similar amplitudes (approximately 35 per-cent peak-to-peak) in both the 940 nm and 830 nm data and appears to be coherent over two periods of the stellar pulsation cycle. Furthermore, the location of the 1992 measurement of Tuthill et al. (1992) suggests that this type of regular behaviour has been sustained over a longer 5-year timescale, i.e. 6 photometric cycles.

A comparison of Fig. 3 with the 940 nm and 830 nm lightcurves (Fig. 2) shows that the maximum apparent size of the star coincided with a visual phase of approximately 0.5 but that the star appeared faintest in the bands observed at close to visual phase 0.55. In both colours the brightest phases of the star corresponded to the smallest angular size. There is perhaps some evidence that the increase in apparent diameter takes place in two phases, i.e. a slow trend at early phases, and then a more rapid increase from visual phase 0.35 to 0.45, but further measurements are needed to confirm this.

3.2 Discussion

Notwithstanding the uncertainties associated with the mapping from an observed angular diameter change to radial motions in a Mira atmosphere, the periodic signature displayed by our measurements implies a direct connection between the apparent stellar diameter and the photometric variability of R Leonis. The issue here is how to link the changes seen to the motions of the stellar atmosphere. The strong wavelength dependence of the monochromatic radii of Mira variables is very well known, with differences as large as a factor of two or three sometimes being seen in specific narrow bandpasses that isolate molecular features in the stellar spectrum (Bessell et al. 1989). The preferential location of these species in the cooler and more extended regions of the stellar atmosphere thus tends to bias any measurements away from the regions where the photospheric continuum is formed.

Both of the filters used for the measurements reported here were broad enough to contain such molecular TiO absorption bands. However, in each case the transmitted flux was dominated by emission from regions of the spectrum with only moderate levels of atomic and molecular blanketing. This is borne out by the fact that both the absolute values and fractional variations of the stellar diameter measured in our two bandpasses were very similar, as was the general consistency of the results obtained in the two other bandpasses (905/50 nm and 880/50 nm). Nevertheless, the precise transformation of the angular displacements reported here to physical motions of the continuum-forming layers remains complicated.

If we adopt the recent parallax for R Leonis of van Leeuwen et al. of 9.87 ± 2.07 mas (1997) then, assuming a linear increase in size, the 940 nm angular diameter measurements imply an expansion velocity of approximately $10\,\mathrm{kms}^{-1}$. The corresponding velocity obtained using the parameters of the Gaussian models is somewhat smaller ($\sim 6\,\mathrm{kms}^{-1}$). This zeroth order approximation, that the angular variations directly trace the photospheric motion, is no doubt far from correct but the order of magnitude of the inferred velocity is in striking agreement with the findings of Hinkle (1978) who used near infrared CO lines to trace the displacement of the photospheric layers in R Leonis.

Further insight can be obtained by comparing our measurements with the recent time-resolved models of Bessell et al. (1996, BSW). These authors address the specific question of the phase and cycle dependence of the apparent diameter of an LPV with the characteristics of the prototype, *o* Ceti. They identify three types of behaviour. First, a small amplitude ($\sim$ 10 per-cent) modulation associated with measurements made using filters isolating near continuum layers, second, aperiodic fluctuations tracing the chaotic motions of shocks in the uppermost cool regions of the atmosphere, and, third, large amplitude ($\sim$ 50 per-cent) variations in bandpasses including weak to medium strength TiO absorption. While some caution needs to be exercised in applying their particular model to R Leonis, which is slightly cooler than Mira, it does appear to correctly predict the order of magnitude of the effect we see.

Within BSW's framework the diameter measurements showing periodic variations (both those tracing near-continuum emission and those in weak to moderately absorbed bands) will be tied to the outward motion of the innermost shock-front in the stellar atmosphere. This leads to a maximum apparent size at phase $\sim$ 0.2 and then a shrinking through and beyond phase 0.5. The observations presented here contradict this prediction, and hint at the possible effects of the strengthening of the TiO bands during the photometric cycle. This is consistent with empirical evidence identifying later spectral types with minimum light (see, e.g. de Laverney at al. 1997), and would imply that our observations represent the combination of this effect with the movement of the inner shock. A critical test of the models of BSW will be to detect the small amplitude variations of the continuum size using high-precision long-baseline interferometry and confirm the small apparent sizes predicted for phase 0.5.

4 SUMMARY

The refinement of dynamical models of LPVs has now allowed the prediction of a number of their observational properties as a function of variability phase. In this paper we have presented new interferometric diameter measurements of the bright Mira, R Leonis, which show, for the first time, the regular large amplitude modulation expected for regions of the spectrum only weakly affected by atomic and molecular absorption. While the magnitude of the variation is as expected, the phase of the observed diameter changes suggests an explanation involving both the location of a periodic shock and a regular variation of the TiO strength. Future models will need to conform with this new observational constraint.

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