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Long-term diameter variations in the long-period variable o Ceti

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ABSTRACT
We report the detection of a large and systematic increase in the angular diameter of the long-period variable o Ceti (Mira). Over the period 1991 September – 1993 December interferometric measurements of the stellar diameter increased by a factor of up to ~ 1.8. The apparent enlargement was most pronounced in bandpasses isolating TiO features, and was far less evident in 'pseudo-continuum' windows largely free from contamination by molecular emission. The time and rate of this event are consistent with models for pulsation-induced mass loss in the star's outer atmosphere. However, the lack of any obvious correlation with the photometric period suggests that the prediction of such events based on the known periodicity of Mira may be difficult, if not impossible.

Key words: stars: – imaging – stars: individual: o Ceti – stars: AGB and post-AGB.

1 INTRODUCTION

The proximity and brightness of the prototypical long-period variable o Ceti (Mira) have made it a favourite target for optical and infrared spatial interferometry. Investigations employing both single telescopes using speckle interferometry (Labeyrie et al. 1977; Welter & Worden 1980; Bonneau et al. 1982), and separated-element Michelson interferometers (Quirrenbach et al. 1992; Ridgway et al. 1992) have provided a plethora of information, mainly in the form of angular diameter estimates at differing optical and near-infrared wavelengths. The enhanced opacity provided by atomic and molecular species in the cool atmosphere of Mira gives rise to a strong dependence of apparent diameter on wavelength (Labeyrie et al. 1977), and so accurate measurements of the stellar diameter as a function of wavelength can provide valuable constraints for models of cool stellar atmospheres (Scholz & Takeda 1987; Bessell et al. 1989).

Recently, high spatial resolution observations of Mira have concentrated on the detection and characterization of asymmetries in its stellar and circumstellar emission (Karovska et al. 1991; Haniff et al. 1992; Wilson et al. 1992; Tuthill, Haniff & Baldwin 1994b). Though well documented, the origins of these asymmetries remain uncertain and they present considerable challenges for the modelling of long-period variable (LPV) atmospheres.

Despite this activity, there have been few attempts to use high-resolution imaging techniques to characterize the spatial properties of Mira as a function of variability phase. The most successful results to date have been those of Quirrenbach et al. (1992) who observed Mira with the Mk III Optical Interferometer (Shao et al. 1988; Mozurkewich et al. 1991) between 1989 October and 1990 November. Their best data, obtained at 800 nm ($\Delta\lambda = 22$ nm) over a three-month period spanning the photometric maximum of 1990 September, were indicative of an asymmetric brightness distribution that showed variability on a time-scale of less than a month. Similar changes in the preferred axis of the photospheric emission from Mira had been identified before (Karovska et al. 1991), but, due to limitations in the temporal coverage of the data available at the time, these early observations were only able to provide upper limits in the range of years for the characteristic time-scales associated with the variation observed.

As part of a long-term programme of optical aperture synthesis imaging, we have been monitoring a number of cool evolved stars over the past three years. In this paper we present multi-wavelength narrow-band angular diameter measurements of Mira obtained between 1991 January and 1993 December. Our observations reveal an unexpected and large increase in the stellar size during this period, which we associate with mass loss induced by a shock propagating through the star's extended atmosphere.

2 OBSERVATIONS AND DATA REDUCTION

Aperture synthesis observations of Mira were obtained at the Ground-based High Resolution Imaging Laboratory (GHRIL) of the 4.2-m William Herschel Telescope at a num-

Table 1. Journal of observations for the period 1991 January to 1993 December. The calendar dates refer to the start of the night of observation and the pulsation phases have been determined from AAVSO records (Mattei, private communication). The photometric maximum prior to the first observation has been arbitrarily assigned to phase 0.00. The data taken in 1991 have already been presented by Wilson et al. (1991) but were independently re-reduced for the purposes of this study. The filter wavelengths are given in nm.

Date (m/y)	JD	Variability Phase (ϕ)	Wavelength $\lambda/\Delta\lambda$
01/91	2448260	0.27	700/10
09/91	2448522	1.07	710/10
	2448523		700/10
01/92	2448640	1.58	700/10
			710/10
			902/50
07/92	2448815	2.05	700/10
			833/41
	2448816		902/50
			700/10
			710/10
			833/41
01/93	2448991	2.47	700/10
	2448992		902/50
09/93	2449238	3.22	700/10
	2449339		710/10
			833/41
12/93	2449328	3.49	700/10
			710/10
	2449329		833/41

ber of epochs during 1991, 1992 and 1993. Similar optical set-ups were employed for all of the experiments. Each utilized a collimating lens placed after the nominal Nasmyth focus to re-image the telescope pupil, an apodizing mask in the pupil plane to select a number of interferometer baselines, and magnifying optics to provide good sampling ($\sim 2\times$ Nyquist) of a refocused image on a fast readout CCD camera. In order to 'freeze' the atmospheric seeing, exposure times of between 10 and 15 ms were used.

At each epoch approximately 20 000 short exposures of Mira were collected through one or more narrow-band filters selected from a set of four. Two of these, centred at 710 and 700 nm, were chosen to isolate a strong TiO bandhead and its neighbouring continuum, while the remaining filters at 833 and 902 nm more nearly sampled the underlying stellar continuum. In view of the long central filter wavelengths and narrow bandpasses, no atmospheric dispersion corrector was used at any epoch.

As in previous experiments (Haniff et al. 1987; Buscher et al. 1990), observations of the source were interleaved with measurements of unresolved calibration stars, and similar observations of a number of well-known binary systems were used to determine the scale and orientation of the CCD. The errors in these quantities were of order a few per cent and 1° respectively. The raw short-exposure images were processed

Table 2. Apparent angular size estimates for Mira derived by fitting circularly symmetric Gaussian models to calibrated Fourier data. Where a number of datasets were secured at a single colour at the same epoch, the average of the FWHM computed for each dataset is shown. The error estimates are formal 1σ errors obtained from the least-squares fitting and do not contain any contributions arising from systematic misfits between the simple models and the data. The units of FWHM are milliarcseconds. No corrections for wavelength-dependent limb darkening or atmospheric extension have been made.

Mean JD −2440000	ϕ	700 nm	710 nm	833 nm	902 nm
8260	0.27	27.3 ± 2			
8523	1.07	30.2 ± 2	33.0 ± 3		
8640	1.58	30.1 ± 2	35.6 ± 3	30.4 ± 3	23.3 ± 2
8816	2.05	27.3 ± 2	31.7 ± 3	28.0 ± 4	22.7 ± 1
8991	2.47	27.6 ± 2			23.0 ± 2
9239	3.22	37.8 ± 2	47.6 ± 3	27.8 ± 3	
9328	3.49	38.2 ± 2	54.8 ± 3	28.8 ± 2	

using standard techniques (Haniff et al. 1987; Buscher et al. 1990) to derive calibrated estimates of visibility amplitudes and bispectra. These were subsequently used for diffraction-limited image reconstruction and model-fitting. A summary of the observations is given in Table 1.

3 RESULTS AND DISCUSSION

3.1 Stellar 'size' variations

It is well established that the estimation of the size of a cool evolved star such as Mira is far from straightforward. Difficulties arise not only because of the range of possible definitions for the stellar radius (Baschek, Scholz & Wehrse 1991), but also because of the strongly wavelength-dependent atmospheric extension and limb darkening expected for such cool stars. More recently, the identification of elliptical isophotes (Karovska et al. 1991; Quirrenbach et al. 1992; Wilson et al. 1992; Tuthill et al. 1994b) and non-centro-symmetric brightness distributions (Haniff et al. 1992; Tuthill 1994) for a number of Mira-type variables has further complicated the issue (see e.g. Tuthill et al. 1994a).

For the purposes of this paper, where our main interest has been in monitoring changes in the extent of Mira's emission rather than establishing its precise physical scale, estimates of the apparent stellar size were obtained by fitting circularly symmetric models to the Fourier data. In general the visibility functions of well-resolved long-period variables are better fitted by Gaussian functions than uniform-disc models (Haniff, Scholz & Tuthill 1995), and so that approach was followed here. In view of the effects of atmospheric extension and limb darkening, the FWHM of these fitted Gaussian models cannot easily be scaled to provide estimates of the stellar continuum photospheric diameter without detailed modelling of the stratification of the stellar atmosphere. However, they still provide a quantitative measure of the extent of the stellar emission, and so hereafter we shall refer to them as apparent diameter measurements.

Observed diameters for Mira for each filter bandpass are presented in Table 2. A noticeable feature of these data is

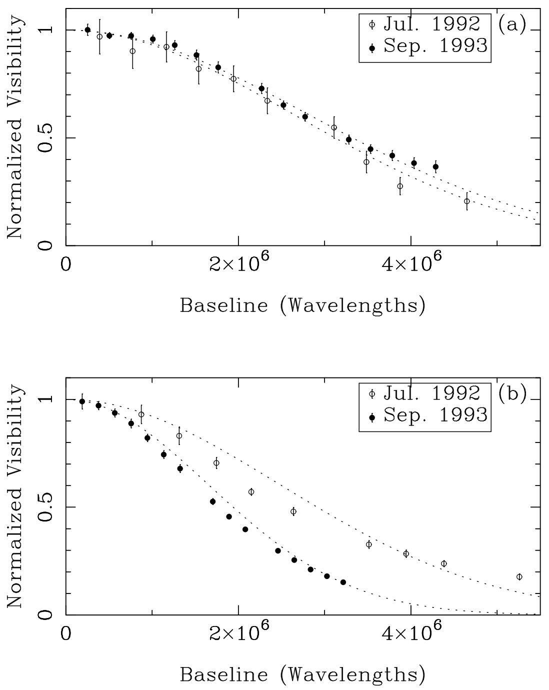

Figure 1. Azimuthally averaged visibility amplitudes for Mira in 1992 July and 1993 September. Panels (a) and (b) show data secured at 833 and 710 nm respectively. For each dataset the best-fitting Gaussian model is shown as a dotted line. In the second panel the poorer fit of the model to the data from 1992 is due to the presence of asymmetric components in the stellar emission contributing $\sim$ 20 per cent of the total flux from the source. When corrected for the presence of these features, the visibility data imply an increase in the size of the symmetric component of the 710-nm image of $\sim$ 15 per cent. At 833 nm the data are consistent with no change in size.

that at any given epoch there were large differences between the measurements obtained in the four bandpasses. Diameters measured at 902 nm were always the smallest, whereas those secured in the TiO absorption band at 710 nm were consistently large. This type of behaviour agrees well with theoretical studies which predict enhanced monochromatic radii at the wavelengths of atomic and molecular species located in the higher, and cooler, regions of the stellar atmosphere (Scholz & Takeda 1987; Bessell et al. 1989). Of the four filters used, the one centred at 902 nm was least contaminated by absorption features and so the measurements in this bandpass were most closely related to the photospheric continuum size of the star.

Of more interest is the behaviour of the apparent size of Mira as a function of time. Over time-scales as short as a few months, variations as large as $\sim$ 15 per cent were sometimes observed. These changes in size were most noticeable in the 710-nm bandpass, and usually much smaller in the pseudo-continuum bands at 833 and 902 nm. One example of this is shown in Fig. 1 which displays the measured visibility amplitudes obtained at two different epochs and wavelengths, together with the visibility functions of the corresponding best-fitting Gaussian models. At 833 nm the visibility data were parametrized well by the Gaussian models, and showed only insignificant differences between the two epochs at which the data were secured. On the other hand the visibility functions measured at 710 nm in 1992 July and 1993 September, though not quite as well described by the Gaussian models, were very different, implying a significant increase in the size of the region emitting at this wavelength.

To assess whether or not the variations in visibility could have arisen from the evolution of discrete components (e.g. bright convection cells) on an otherwise unchanging stellar disc, the visibility data were examined for evidence of asymmetric features in the stellar emission. This is a powerful method for detecting surface inhomogeneities because there is no a priori reason to suppose that they should be symmetrically disposed on the stellar surface, and so only in the unlikely case of a hotspot located at the centre of the stellar disc will the apparent symmetry of the stellar emission be preserved. The tell-tale signs of such asymmetric structures are variations of visibility amplitude as a function of position angle on the sky and the presence of non-zero bispectrum phases. In fact non-zero bispectrum phases were unambiguously detected at a number of epochs (1992 July, 1993 September and 1993 December) when the data quality was sufficiently good. At these times the bispectrum phases exhibited systematic excursions from the value of 0° expected for a symmetric source and were sometimes as large as $\pm 35^\circ$. If interpreted in terms of models comprising a small number (one or two) of compact features superposed on a circularly symmetric disc, these values correspond to unresolved hotspots emitting between 5 and 15 per cent of the total flux from the star. Not surprisingly, the visibility amplitudes measured at these epochs also showed systematic modulations as a function of position angle, particularly on the longest baselines.

Under these circumstances the fitting of a simple circularly symmetric Gaussian model to the visibility amplitudes, rather than a more complex model chosen to satisfy the constraints set by the measured bispectrum phases, will underestimate the true size of the disc component emission. However, at 833 and 902 nm the extents of the symmetric stellar emission estimated using both the simple and more complex models never differed by more than 10 per cent, though at 700 and 710 nm the differences were somewhat larger (between 15 and 20 per cent).

The presence of asymmetric components of the stellar brightness distribution will thus have led to systematic differences between the diameter estimates in Table 2 and the true stellar diameter. However it seems unlikely that this can have accounted for the most interesting feature of our data, i.e. the large and rapid *variation* in the stellar size and its wavelength dependence. Over the period of our observations the asymmetric component of the stellar emission was strongest in 1992 July when it contributed $\sim$ 20 per cent of the total flux from the source. By 1993 January this had declined to no more than $\sim$ 5 per cent, and between September and December of the same year it varied between 9 per cent and 13 per cent. The fact that only moderate changes in the asymmetric source flux were detected during 1993, despite the large variations of Mira's visibility function observed over the same period, strongly suggests that the measurements presented in Table 2 do reflect the effects of a real change in the extent of the stellar atmosphere, rather than the consequences of a localized event such as the ejection of a blob of gas or dust, or the waxing and waning of a surface hotspot.

3.2 Physical interpretation

There seems little doubt that the diameters presented in Table 2, though derived using a simplistic model for the stellar brightness distribution, reflect true changes in the extent of Mira's atmosphere. These variations, presented graphically in Fig. 2, show a number of unusual features. Most importantly the variability amplitude was a strong function of wavelength. In the bandpasses most sensitive to photospheric emission, at 833 and 902 nm, only small changes in the stellar diameter were detected, whereas at shorter wavelengths much larger variations were evident, particularly within the 710-nm filter bandpass which is centred on a strong TiO absorption feature. However, because of the presence of a strong asymmetric component in the stellar emission in 1992 July ($\phi = 2.05$), the data shown in Fig. 2 are somewhat ambiguous with regards to the overall magnitude and time-scale of the 'expansion' of Mira detected during the period of our observations. At a single epoch (1992 July), corrections to account for the contribution of the asymmetric emission to the visibility function increased the best-estimates of the stellar diameter from 32 to 47 mas at 710 nm, and from 27 to 32 mas at 700 nm. The correction factors for all the other data, i.e. at all epochs and for all colours, were considerably smaller than this and so, apart from the two data points mentioned above, a plot of the corrected data reproduces the same trends as shown in Fig. 2. With these corrections in place, our data thus indicate an approximately linear increase in the stellar diameter at 710 nm of 85 per cent between 1991 September ($\phi = 1.07$) and 1993 December ($\phi = 3.49$). Unfortunately, the absence of a measurement at 710 nm in 1993 January ($\phi = 2.47$) means that we have been unable to eliminate an alternative, though perhaps less likely, possibility, i.e. that the behaviour of the stellar diameter at 710 nm between 1992 July and 1993 January mirrored that at 700 nm by falling before rising again towards the latter part of 1993. This would imply an increase in the stellar diameter at 710 nm of similar magnitude to that described above, but compressed into a time-scale of only some 12 months, as compared to 25. Notwithstanding this uncertainty, one aspect of the observed diameter fluctuations that deserves comment is the lack of any obvious relationship with the variability period. While our data extend over only 4 periods of the photometric cycle, measurements secured at comparable phases during differing cycles showed little correlation. For example, the diameter measurements obtained in 1993 January ($\phi = 2.47$) and 1993 December ($\phi = 3.49$) correspond to very similar variability phases yet differ by a factor of 35 per cent at 700 nm, and presumably even more at 710 nm.

Earlier published data shed little light on these aspects of Mira's atmosphere. The observations reported by Karovska et al. (1991) were only sensitive to fluctuations on very long time-scales ($\gg$ the 332-d photometric cycle) and were dominated by the effects of asymmetric features in the atmosphere. Quirrenbach et al. (1992) were able to detect a decrease in the stellar size around the photometric maximum in 1990 November, but the interpretation of their data is complicated because of the variation of TiO opacity within their 22-nm bandpass. Using a rudimentary two-component model, they inferred a decrease in the continuum diameter of Mira of approximately 20 per cent over a 33-d period, but, given the limited UV coverage and wavelength resolution of their observations, they caution the reader on the reliability of this interpretation.

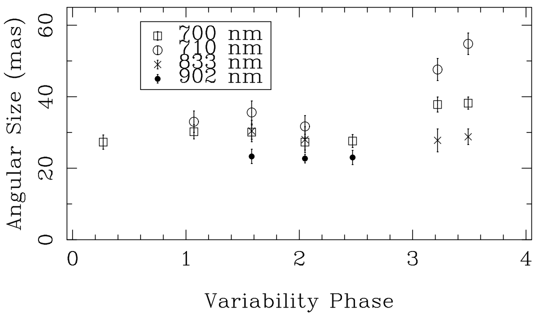

Figure 2. Mean angular diameter estimates ($\equiv$Gaussian FWHM) for Mira at 4 wavelengths. These are plotted against variability phase, where a period of 332 d has been assumed. The first datum at $\phi = 0.27$ corresponds to JD 244 8260 (1991 January).

Despite the lack of any clear correlation with the photometric period, it seems highly likely that the fundamental process responsible for the diameter variations reported here is the pulsational instability that underlies Mira's photometric variations. Within this framework two types of behaviour can be distinguished. The first of these relates to the most direct manifestation of the stellar pulsation, i.e. the expected periodic modulation of the stellar photospheric layers. Time-dependent models of the radial structure of Mira atmospheres (see e.g. Hill & Willson 1979; Bowen 1988) usually incorporate this as a boundary condition, with the inner boundary radius of the model being forced to oscillate quasi-sinusoidally with moderate ($\sim$ 20 per cent) amplitude. This assumption has been questioned by Hill & Willson (1979), but the agreement between the predictions of these and other models and observations suggests that it is unlikely to be grossly incorrect.

Unfortunately, direct observational verification of the expected periodic changes in the photospheric diameters of Mira variables has been difficult to achieve. Measurements obtained using speckle interferometric techniques have usually been compromised by the effects of limb darkening and the fact that the visible spectra of Mira variables are dominated by atomic and molecular lines (see e.g. Scholz & Takeda 1987). Radial velocity (Hinkle, Hall & Ridgway 1982) and bolometric magnitude and effective temperature (Tuthill et al. 1994a) measurements provide more indirect methods for estimating the stellar diameter, but these are relatively imprecise and suggest periodic variations in the range 10 to 50 per cent. Of the four filters used for this study, the one centred at 902 nm should have been least contaminated by absorption features, and hence most sensitive to the periodic modulation of the photospheric layers. However, the individual measurements at any epoch had relatively large errors ($\sim$ 7 per cent) and so the unambiguous detection of any small-amplitude periodic variations in the stellar continuum diameter has not been possible.

In addition to these moderate modulations, much larger, though still periodic, diameter changes are expected due to the propagation of shock fronts through the extended stellar atmosphere (Wood 1979; Willson & Hill 1979; Bowen 1988). These lead to discontinuities in the otherwise smoothly declining atmospheric density gradient which, coupled with the effects of local heating, manifest themselves via the presence of strong line emission and large fluctuations in the monochromatic stellar diameter (Scholz & Takeda 1987; Beach, Wilson & Bowen 1988; Bessell et al. 1989). As mentioned above, it is difficult to reconcile our measurements with a strictly periodic phenomenon. However, an *aperiodic* shock model with an expanding shell of enhanced density propagating out into the circumstellar environment is entirely consistent with our data. In this case the large systematic increase in size detected between 1991 September and 1993 December can be understood in terms of a change in the location of a diffuse symmetric shell of material scattering most strongly at those wavelengths for which the atmosphere had high optical depth, i.e. in the metal oxide bands. The low level of asymmetry detected in the data obtained between 1993 January and 1993 December agrees with this scenario, and argues against the possibility of the ejection of any discrete blobs of material. Furthermore, the sensitivity of the observed diameter variations to colour are naturally explained in this model in terms of the wavelength dependence of the atmospheric opacity.

It is unfortunate that dynamical models of Mira atmospheres present conflicting predictions for the repeatability of this type of phenomenon, with for example Drinkwater & Wood (1985) predicting strong aperiodic shocks but with the more recent models of Bowen (1988) suggesting very regular behaviour. While the evidence for shock propagation in Mira atmospheres (see e.g. Wood 1979; Hill & Willson 1979; Hinkle et al. 1982; Bowen 1988) is not in doubt, the existence of aperiodic pulsation in the outer layers above the photosphere would help to explain a number of earlier observations. The velocities of metallic absorption lines have long been known to show only a weak correlation with pulsation phase (Joy 1954). This has been interpreted as indicating aperiodic behaviour in the shocks at upper atmospheric levels (Hill & Willson 1979). In addition, circumstellar absorption lines indicative of multiple discrete expanding shells around mass-losing stars (Bernat 1981; Ridgway 1981) are consistent with the picture of mass driving by occasional coalesced shocks.

The presence of an aperiodic shock is thus an attractive explanation for the observed enlargement of Mira on a number of accounts. The fact that previous high spatial resolution observations of the star (despite their sparse temporal coverage) have not revealed similar large fluctuations in apparent size (see for example Karovska at al. 1991; Wilson et al. 1992) is consistent with such a model. Furthermore, assuming a distance estimate of 110 pc (Haniff et al. 1995), the observed changes in angular size correspond to linear velocities of $\sim 5\ \mathrm{km\,s^{-1}}$. These certainly correspond in magnitude to the post-shock outward velocities predicted on the basis of numerical models, although the observed diameter variations are likely to be due to a complex combination of physical motion and changing physical conditions, such as density and heat input/output, rather than to simple ballistic motion of well-defined parcels of gas.

Further evidence for the presence of a shell of cool material propagating outwards from Mira during 1992/1993 would have been the occurrence of a fainter than expected photometric maximum in 1994. Unfortunately amateur records (Mattei, private communication) of the visual magnitude of Mira are incomplete at just this time due to an inopportune conjunction of Mira and the Sun. Nevertheless, mid-infrared spectroscopy and interferometric data do suggest significant changes in both the form and intensity of the dust emission from the star between 1994 August and 1995 January (Townes, private communication), which may be related to the phenomenon we have detected.

4 SUMMARY

We have shown that interferometric angular diameter measurements can be used to probe the dynamical behaviour of the atmospheres of LPVs. Multi-colour observations of the prototypical source *o* Ceti taken at intervals during the period 1991 January – 1993 December indicate an unexpected increase in the apparent size of the star at wavelengths sensitive to the cooler regions of the stellar atmosphere. Measurements of deeper photospheric layers, however, show no such variation, thereby suggesting the presence of an expanding shell of cool circumstellar material. The systematic and sustained increase in apparent size over this period appears to rule out any mechanism strictly locked to the photometric variability cycle. It seems most likely that these data are the manifestation of an aperiodic shock front propagating through the stellar atmosphere. The magnitude of this event, which led to an apparent change in the monochromatic stellar diameter of ~ 85 per cent over a 25-month period, implies that further similar events should be readily detectable in other Mira-type stars, albeit at unpredictable times.

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