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Interferometry of pulsating red giants from 0.65 to 3.5 microns

Michael Ireland[1], Peter Tuthill[1], Gordon Robertson[1],
Timothy Bedding[1], Andrew Jacob[1], John Monnier[2], William Danchi[3]

[1]*School of Physics, University of Sydney, NSW 2006, Australia*
[2]*University of Michigan, Ann Arbor, MI, USA*
[3]*NASA Goddard, Infrared Astrophysics, Greenbelt, MD 20771, USA*

Abstract. We present the results of two multi-wavelength studies of the angular diameters of the Mira-like stars *o* Cet, W Hya and R Leo. The MAPPIT experiment was able to deliver diameters of these stars over a continuous wavelength region from 0.65 – 1 micron, while the Keck aperture-masking experiment was able to deliver diameters between 1.2 and 3.5 microns. Strong size variations with wavelength were recorded for all stars, and we discuss the implications for model atmospheres of these stars, and speculate on the necessity of including dust scattering in radiative transfer calculations.

1. Introduction

There has been a wealth of interferometric observations of Mira-like stars, as reviewed in Scholz (2003) and Monnier (2003), which demonstrate dependencies of diameter on wavelength, pulsation phase and pulsation cycle. Many measurements of diameter have been larger than those predicted by fundamental-mode pulsation models, causing several authors to suggest that Mira-like stars must pulsate in an overtone mode (e.g. Haniff, Scholz & Tuthill 1995; Weiner, Hale & Townes 2003). This contradicts the conclusions drawn from pulsation velocities (Scholz & Wood 2000) and period-luminosity relationships in the large Magellanic cloud (Wood et al. 1999). The data set presented here sheds some light on this controversy.

2. Observations and Data Reduction

MAPPIT (Masked APerture Plane Interference Telescope) was an aperture masking system set up at the Anglo-Australian Telescope (AAT). The pupil of the AAT was re-imaged onto a mask, with starlight subsequently passing through a prism and cylindrical lens, as described in Jacob et al. (2003). The optical setup resulted in the image formed at the detector having high resolution spatial information (fringes) in one direction, and a spectrum of the source from 650 nm – 1 μm in the other. The Keck aperture-masking experiment was used in two modes. In the first, fringes were formed through 2-dimensional non-redundant masks and narrow-band J, H, K and L filters, as described in Tuthill et al.

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(2000). In the second mode, fringes were formed through a 1-dimensional mask, slit and grism. This produced wavelength-dispersed fringes as in the MAPPIT experiment although motion of the image on the spectrograph slit meant that reliable calibration could not be obtained from 1-dimensional masking data alone. The visibility curves of the 1-dimensional dispersed data were absolutely calibrated using azimuthally-averaged visibility curves from 2-dimensional data at the narrow-band filter wavelengths taken on the same night. The MAPPIT experiment did not suffer from this problem as the cylindrical lens in the optical setup meant the spectrograph slit was in the pupil plane (see Bedding et al. 1994).

The fringes at each wavelength are processed via a Fourier transform to give visibility as a function of baseline length. A drop in visibility on long baselines indicates the star is resolved and allows us to measure its angular size. The measurements of angular diameter were calibrated by interleaving observations of an unresolved star to correct for residual atmospheric effects. For the MAPPIT data in particular, a Gaussian profile gave a better fit to the visibilities than a uniform or limb-darkened disk. This is indicative of significant wings in the brightness distribution. Gaussian Full-Width Half Maxima (FWHM) are presented as a function of wavenumber in Fig. 1. The times and phases of these observations is given in Table 1.

Table 1. Times and phases of the observations presented here. All MAPPIT data were taken on the nights of 2001 February 8/9.

Name	Pulsation Phase (MAPPIT)	Observation Date (Keck)	Pulsation Phase (Keck)	Period (d)
o Cet	0.34	2002 Jul	1.95	332
R Leo	2.91	1999 Apr	0.74	310
W Hya	1.43	2000 Jan	0.44	361

3. Discussion

As the short- and long-wavelength observations are not contemporaneous, they cannot be directly compared, however the R Leo and W Hya Keck and MAPPIT data are at a similar phase, despite being in a different cycle. Separate Keck data sets on W Hya (not shown) at a variety of pulsation phases only show a 10% variation of diameter about the mean, implying that, at least for this star, the Keck observations would be expected to be similar if they had been contemporaneous with the MAPPIT observations.

The most noticeable feature of the diameter versus wavelength plots of Fig. 1 is the large increase in apparent size in the molecular absorption bands of H_2O and CO between 1.5 and 3.5 μm, and in the TiO absorption bands at wavelengths shorter then 1 μm. The extent of this variation in diameter for *o* Cet cannot be reproduced by even the most extreme models investigated in Jacob & Scholz (2002). For R Leo we have plotted the average of four near-maximum fundamental-mode P model diameters corresponding to our baselines

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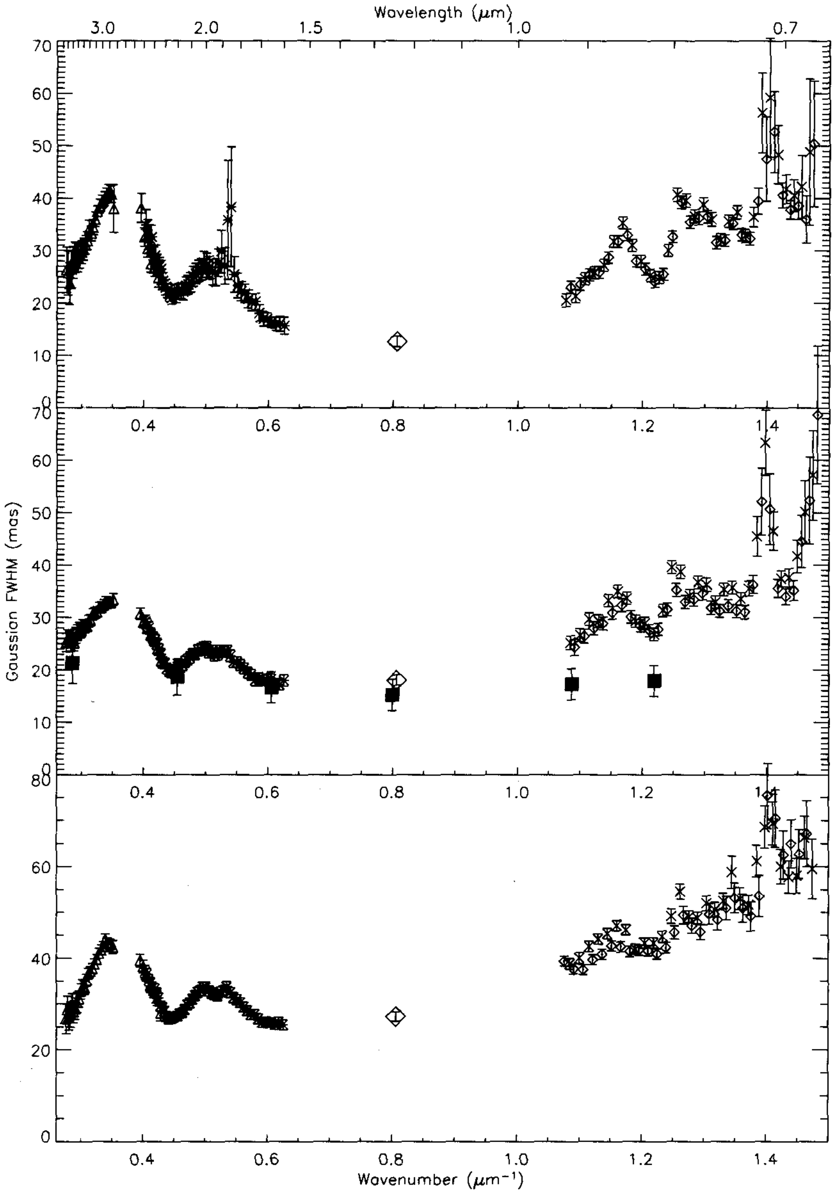

Figure 1. Gaussian FWHM as a function of wavenumber (wavelength shown on upper horizontal axis for reference) for *o* Cet (top), R Leo (middle) and W Hya (bottom), from both the MAPPIT and Keck experiments. See Table 1 for times and phases of observations. The filled squares in the central plot represent an average diameter for P models from Jacob & Scholz (2002) (see text).

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and fitting procedure from Jacob & Scholz (2002) (filled squares). We used the Hipparcos parallax for this. These averaged model diameters fit the observed near-infrared diameters but do not reproduce the increase in near-continuum diameter below 1 μm. Note that these models do not include the effects of scattering by dust, and are not tailored for R Leo, but only designed as a generic Mira-like model atmosphere. The second important feature of these plots is the general increase in diameter toward blue wavelengths. For W Hya in particular, this is clearly not associated with molecular features, and must be associated with a source of continuum opacity. We interpret this as being scattering by dust in the outer atmosphere. If this effect is common to all Mira-like stars with significant dust production, then it could resolve the discrepancy of the larger than expected short-wavelength diameters without appealing to overtone pulsation. This also helps to explain the Gaussian-like appearance of visibility curves at shorter wavelengths, and the inability for dust-free models to explain the observed short-wavelength diameters. This explanation for the anomalous short-wavelength measurements has also been cited by Danchi et al. (1994) and Hofmann et al. (2001). Further work at the shorter wavelengths can be found in Ireland (2004), where a larger sample of Mira-like stars are investigated, including some with wavelength-dependent asymmetries.

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Discussion

Habing: The dust scattering that you map seems to occur quite close to the photosphere, closer than current theories of dust formation predict. Is this impression correct?

Ireland: The observations I presented can be explained by an inner radius of dust formation around 2 "continuum" radii, but I am yet to do a full comparison with models. This dust formation radius is consistent with the observations of Danchi et al. (1994) and the model study of Bedding et al. (2001).

Wing: I don't understand why you want to attribute the trend with wavelength to the effects of dust when it is just what you would expect form TiO. In addition to the feature at 710 nm, TiO opacity generally increased to shorter wavelengths and is greater in the visual region than in the 710 nm band. A good test would be to push the observations to shorter wavelengths. At 410 nm, the TiO absorption goes away, but the dust does not.

Ireland: I agree that it is difficult in general to disentangle the effects of TiO and dust in general, and requires more detailed modelling. However, I'd like to point out W Hya again, where there was relatively little diameter variation both in the 712 nm TiO band and the 3 μm water feature, but there was a large increase in diameter toward shorter wavelengths. An extended molecular atmosphere cannot produce these effects together. Observations at 410 nm have not been possible because seeing effects cause signal-to-noise to be a very strong function of λ, but will be possible with the next generation of experiments within 1–2 years.

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