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Cyclic variations in the angular diameter of χ Cygni

J. S. Young,[★] J. E. Baldwin, R. C. Boysen, C. A. Haniff, D. Pearson, J. Rogers, D. St-Jacques,[†] P. J. Warner and D. M. A. Wilson

Astrophysics Group, Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE

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ABSTRACT

We report the direct detection of cyclic diameter variations in the Mira variable χ Cygni. Interferometric observations made between 1997 July and 1999 September, using the Cambridge Optical Aperture Synthesis Telescope (COAST) and the William Herschel Telescope (WHT), indicate periodic changes in the apparent angular diameter at a wavelength of 905 nm, with amplitude 45 per cent of the smallest value. The star appears largest at minimum light. Measurements made at a wavelength of 1.3 μm over the same period suggest much smaller size changes. This behaviour is consistent with a model in which most of the apparent diameter variation at 905 nm is caused by a large increase in the opacity of the outer atmospheric layers (which is mostly owing to titanium oxide) near minimum light, rather than by physical motions of the photosphere. The 1.3-μm waveband is relatively uncontaminated by TiO, and so much smaller size changes would be expected in this band. The latest non-linear pulsational models predict maximum physical size close to maximum light, and increases in opacity near minimum light that are too small to reproduce the diameter variation seen at 905 nm. This suggests either that the phase-dependence of the model pulsation is incorrect, or that the opacities in the models are underestimated. Future interferometric monitoring in uncontaminated near-infrared wavebands should resolve this question.

Key words: techniques: interferometric – stars: AGB and post-AGB – stars: individual: χ Cygni – stars: oscillations – stars: variables: other.

1 INTRODUCTION

Despite the length of time for which they have been studied, long-period variable stars remain enigmatic objects. In the sub-class of Mira variables, stellar pulsation can cause huge photometric variations (up to 11 mag in the *V* band), but because of the paucity of direct observations the main characteristics of the pulsation are still undetermined. In particular, neither the pulsation amplitude nor the visual phase corresponding to maximum physical size have been measured. Whether the stars pulsate in the fundamental or first-overtone radial mode also remains contentious (see, e.g. Barthès 1998; Ya'ari & Tuchman 1999).

Of these issues, the question of the mode of pulsation has received the most attention from interferometric researchers, as in principle a single diameter measurement can indicate the particular mode excited in any given Mira (Haniff, Scholz & Tuthill 1995; van Belle et al. 1996; van Leeuwen et al. 1997). Further details of the pulsation, though, require diameter measurements throughout the variability cycle, at phases where the star can be very faint at visible wavelengths and interferometric observations difficult to secure.

Diameter changes in Mira-variable stars have previously been measured by van Belle et al. (1996), who found variations with phase within a sample of one- or two-epoch measurements of 18 stars, and by Tuthill, Haniff & Baldwin (1995), who made seven observations of *o* Ceti spread over a three-year period. However, the first direct detection of cyclic variations in the apparent diameter of an individual Mira was made by Burns et al. (1998, henceforth B98), who carried out 18 observations of R Leonis with the Cambridge Optical Aperture Synthesis Telescope (COAST) (Baldwin et al. 1998) and the William Herschel Telescope (WHT) over a 16-month period in 1996 and 1997.

Unfortunately, the Burns et al. measurements of R Leonis only covered half of the pulsation cycle at two closely spaced wavelengths, and so to allow better discrimination of existing atmospheric models we initiated a programme of diameter measurements of the Mira variable χ Cygni in mid-1997. This nearby Mira has an unusually large photometric amplitude, suggesting perhaps a large pulsation amplitude, and its high

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[★] E-mail: J.S.Young@mrao.cam.ac.uk

[†] Present address: National Astronomical Observatory, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan.

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 92/07/13 have been reported previously (Haniff et al. 1995). The visual phases were calculated using the ephemerides from the 1997, 1998 and 1999 Observer's Handbooks of the Royal Astronomical Society of Canada. N_{vis} and N_{cl} refer to the number of visibility and closure-phase measurements made. An identical number of visibility measurements were made for the calibration source. Each 'measurement' corresponds to 30–60 s of data.

Date(s)	Telescope	Pulsation phase	Baseline range (m)	905 nm		1290 nm	
				N_{vis}	N_{cl}	N_{vis}	N_{cl}
92/07/13	WHT	0.32	0.5–3.5	28	15	–	–
97/07/19, 20	COAST	4.83	4.0–8.4	–	–	11	–
97/07/20	COAST	4.83	4.0–8.0	6	–	–	–
97/08/07	COAST	4.87	3.5–8.2	29	25	–	–
97/08/11	WHT	4.88	0.3–3.7	90	90		–
97/08/25, 27, 30	COAST	4.92	4.0–8.3	12	–	–	–
97/09/22	COAST	4.99	3.6–8.2	9	–	–	–
97/10/05	COAST	5.02	4.3–7.9	–	–	5	–
97/10/18	COAST	5.05	3.5–8.0	12	–	–	–
97/12/03	COAST	5.16	3.6–7.9	6	–	–	–
98/05/16	COAST	5.61	4.1	1	–	–	–
98/07/13	COAST	5.75	4.7–5.1	5	–	–	–
98/07/16	COAST	5.76	9.4	–	–	1	–
98/07/18	COAST	5.76	5.0–20.5	–	–	32	–
98/07/24	COAST	5.78	4.5–5.2	9	–	–	–
98/08/04	COAST	5.80	5.5–5.6	6	–	–	–
98/08/04	COAST	5.80	4.4–10.7	–	–	14	–
98/08/18	COAST	5.84	4.7–5.2	9	–	–	–
98/08/19	COAST	5.84	5.0–20.5	–	–	–	17
98/09/19	COAST	5.92	4.4–4.6	20	–	–	–
98/10/14	COAST	5.98	4.4	10	–	–	–
98/10/18	COAST	5.99	4.7–5.2	9	–	–	–
98/12/06	COAST	6.11	4.5–4.7	26	–	–	–
99/08/21	COAST	6.70	5.4–5.5	3	–	–	–
99/09/05	COAST	6.74	5.0	2	–	–	–

declination allows it to be observed with COAST for nine months of its 13-month variability cycle.

In this paper we present the first results of this programme. Measurements made at a wavelength of 905 nm exhibit phase-coherent changes similar to the variations previously seen in R Leonis, now with coverage of most of the pulsation cycle. However, our data in a 1.3-μm waveband less affected by TiO absorption show different behaviour, and suggest that most of the change in apparent size seen in moderately-blanketed passbands is owing to changes in opacity rather than physical motions of the photosphere.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Measurements with COAST

χ Cygni was monitored with COAST in two wavebands, selected using interference filters with centre wavelengths and half-power bandwidths of 905/50 nm and 1306/260 nm (a standard *J*-band filter). In practice the *J* passband was modified by strong telluric absorption towards the red, giving an effective wavelength of 1290 nm and a bandwidth of 150 nm.

Observations were secured on 25 nights covering almost two consecutive 407-d pulsation cycles in 1997, 1998 and 1999, during which time four of the COAST telescopes were operational. The dates of the observations together with further details are given in Table 1. At 905 nm the primary mirrors were stopped down to a diameter of 16 cm to better match the seeing conditions ($r_0 \sim 10$ cm at this wavelength), whereas at 1.3 μm, aperture sizes of either 24 or 40 cm were used.

The beams from the unit telescopes were combined and focused onto single-element detectors, either avalanche photo-diodes in the optical or single pixels of a NICMOS3 infrared detector. The observations at 905 nm used the standard COAST beam-combiner, whereas those at 1.3 μm were obtained with a separate pupil-plane combiner optimized for the *JHK* bands (Young et al. 1998; Young 1999). The interference fringes were recorded by the usual method of scanning the optical path of one or more of the input beams to create a temporal fringe pattern, which was subsequently sampled by the detectors at rates of 1–5 kHz.

The observations of χ Cygni were interleaved with observations of a calibrator star, one of either η Cygni, β^1 Cygni or α Lyrae. Visibility amplitudes were measured on all baselines on which fringes could be detected, with each baseline being measured separately so as to obtain the optimum signal-to-noise ratio. If at least three baselines were measurable, and the atmospheric coherence time was sufficiently long, then closure phase measurements were also secured. The layout of the COAST array was changed in 1998 January, increasing the maximum baseline from 8 to 20 m. The longer baselines were ideal for observations of χ Cygni at 1.3 μm, but at 905 nm fringes could only be detected on the shortest (5.6-m) baseline.

Standard procedures (Burns 1997; Burns et al. 1997) were used to reduce the COAST data, with the power spectra and bispectra of the fringes being averaged over each data stream to obtain estimates of the visibility amplitudes and closure phases respectively. Since the calibrator star β^1 Cygni was slightly resolved on the 20-m baseline at 1.3 μm (β^1 Cygni was not used as a long-baseline calibrator at 905 nm) the relevant visibilities were corrected assuming an adopted diameter for this calibrator. A value of 4.8 milliarcsec was used based on the angular diameter-*V*–*K* colour relationship for K-type giant stars of Di Benedetto (1993). This correction increased the Gaussian full width at half-maximum (FWHM) inferred from the 1998 July 18 data by just 2 per cent and so is unlikely to have biased the results presented here in any significant way.

2.2 Measurements with the WHT

Further interferometric measurements of χ Cygni were made in 1997 August 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). Data from a similar experiment performed in 1992 July (Haniff et al. 1995) is also used in this paper. In both cases, an aperture mask was inserted in a re-imaged telescope pupil to convert the WHT into an interferometer array. Differing masks were used to select a number of interferometer baselines, the resulting fringe patterns being sampled on a fast-readout CCD. Linear four- and five-hole masks were used, which were rotated relative to the sky to increase the number of separate visibility amplitudes and closure phases measured. Details of the observations are given in Table 1.

3 RESULTS AND DISCUSSION

3.1 Angular diameters

In order to characterize the stellar size, we chose to fit Gaussian models for the brightness distributions to the visibility amplitude data. This type of model was found to better fit all the datasets incorporating long-baseline measurements, i.e. where the visibility amplitude fell below 30 per cent (see e.g. Fig. 1) than uniform disc models.

In principle, the diameters inferred by fitting one-parameter models may be biased by departures of the stellar disc from circular symmetry. In particular, asymmetric brightness distributions have previously been detected in Mira variables at optical wavelengths. These have been modelled as either elliptical discs (Karovska et al. 1991; Haniff et al. 1992; Quirrenbach et al. 1992; Wilson et al. 1992; Weigelt et al. 1996), or a few unresolved features superimposed on a circular disc (Haniff et al. 1995; Tuthill, Haniff & Baldwin 1999). Note that departures from reflection symmetry cannot be detected interferometrically if the Fourier phase information is missing or of poor quality, in which case an elliptical disc model would be chosen.

To investigate this potential cause of bias, where non-unit visibility amplitudes were measured on two or more baselines with different orientations, elliptical Gaussian and uniform disc models were fitted to the data. In all cases, there was no evidence for departures from circular symmetry. Where the data sets included closure phase measurements, we also attempted to fit models consisting of a disc plus one or two unresolved features. The disc diameters in the best-fitting such models were all within 6 per cent of the diameters inferred using Gaussian discs alone, and suggest that, in the absence of any *a priori* evidence, a reasonable assessment of the uncertainty in the angular diameter associated with this type of ambiguity is of the order of 5 per cent.

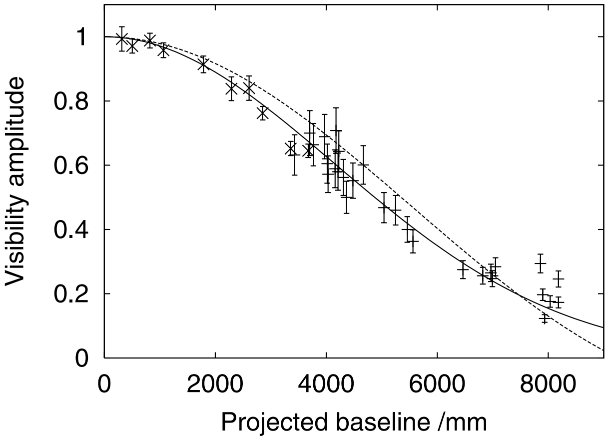

Figure 1. Visibility curve for χ Cygni at 905 nm. The vertical crosses are visibility amplitude measurements from COAST on 1997 August 7, and the diagonal crosses are averages of nine WHT measurements, at different baseline orientations, from 1997 August 11. The visual pulsation phase on these dates was 0.87. The best-fitting Gaussian (solid line) and uniform disc (dashed line) models are also shown. The Gaussian model is clearly a better fit to the data.

Table 2. Apparent angular sizes (Gaussian FWHM intensity) and 1σ errors for χ Cygni at 905 nm and 1290 nm. The WHT measurement from 1992 July 13 is that of Haniff et al. (1995).

Date	Pulsation phase	Telescope(s)	Gaussian FWHM (mas) 905 nm	Gaussian FWHM (mas) 1290 nm
92/07/13	0.32	WHT	19.6±1.5	–
97/07/19	4.83	COAST	–	13.9±0.8
97/07/20	4.83	COAST	15.9±0.4	–
97/08/07	4.87	WHT + COAST	16.9±0.2	–
97/08/27	4.92	COAST	16.1±0.2	–
97/09/22	4.99	COAST	15.3±0.2	–
97/10/05	5.02	COAST	–	13.4±0.4
97/10/18	5.05	COAST	16.0±0.2	–
97/12/03	5.16	COAST	18.3±0.2	–
98/05/16	5.61	COAST	22.5±1.9	–
98/07/13	5.75	COAST	20.4±0.4	–
98/07/16	5.76	COAST	–	12.3±0.9
98/07/18	5.76	COAST	–	12.2±0.1
98/07/24	5.78	COAST	20.8±0.5	–
98/08/04	5.80	COAST	19.4±0.2	12.1±0.3
98/08/18	5.84	COAST	16.8±0.4	–
98/09/19	5.92	COAST	17.2±0.6	–
98/10/14	5.98	COAST	17.0±0.1	–
98/10/18	5.99	COAST	16.7±0.2	–
98/12/06	6.11	COAST	14.3±0.3	–
99/08/21	6.70	COAST	20.7±0.5	–
99/09/05	6.74	COAST	18.1±0.8	–

The 1998 and 1999 observations at 905 nm were all obtained using a single baseline, and the reader should note that the presence of an otherwise unknown unresolved feature contributing 10 per cent of the total flux from the source would have biased our fitting by up to 15 per cent, in either direction (although the feature would have to be very close to the stellar limb to *increase* the inferred diameter by this amount). In view of both the repeatable and large cyclic behaviour exhibited by our apparent diameter measurements, it is likely that the presence of random asymmetries, even at this level, has not been a major source of bias in our analysis.

Our main result, the temporal behaviour of the apparent angular size of χ Cygni as measured at 905 nm, is presented in Table 2 and Fig. 2. Our data clearly indicate that the apparent angular size varies in a phase coherent manner, with the diameter increasing

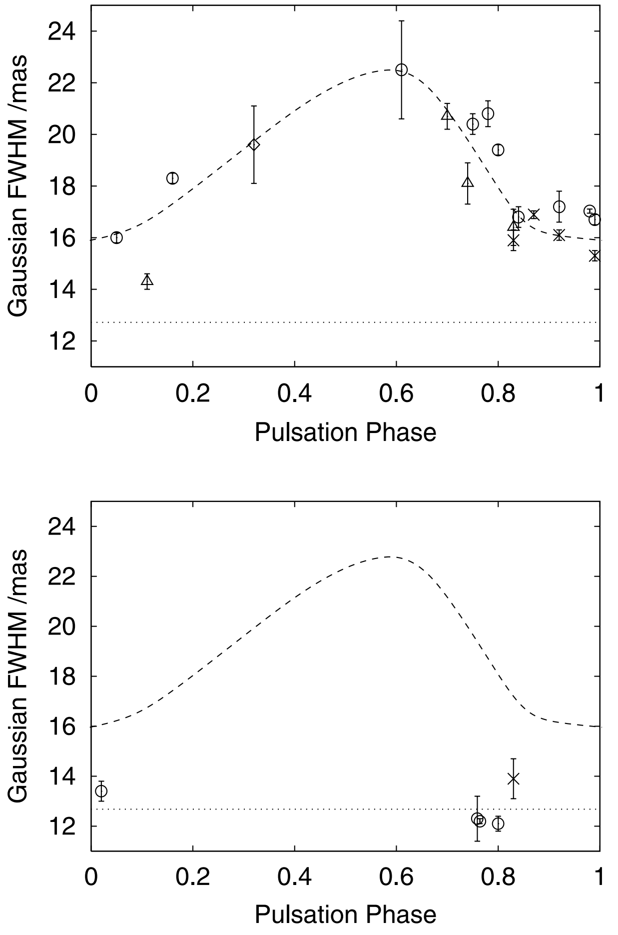

Figure 2. Apparent angular sizes (Gaussian FWHM intensity) and 1σ errors for χ Cygni at 905 (top) and 1290 nm (bottom), plotted against the phase of the visual light-curve (zero represents maximum visual light). Three consecutive cycles have been folded into a single plot: crosses indicate 1996–7 measurements, circles 1997–8 measurements, and triangles 1998–9 data. The diamond at phase 0.32 is the 1992 measurement at 902 nm of Haniff et al. (1995). The 905-nm diameter increases slowly from phase 0.0 to phase ~0.5, decreases rapidly between phases 0.6 and 0.8, then stays approximately constant up to maximum light. This generic variation is indicated by the dashed line, which is reproduced in the lower plot to highlight the very different behaviour at 1290 nm. A similar slow diameter increase during the first half of the pulsation cycle is seen in the B98 measurements of R Leonis. The dotted line (also superimposed on the 905-nm plot) roughly indicates the mean 1290-nm diameter.

slowly from phase 0.0 to phase ~0.5, decreasing rapidly between phases 0.6 and 0.8, then remaining approximately constant up to maximum light. The peak-to-peak amplitude of the variation is approximately 45 per cent of the smallest diameter. In general this behaviour is repeated from year to year, though there are small cycle-to-cycle differences discernible in the data, for example the rapid diameter decrease after minimum light occurs earlier in 1999 than in 1998. Interestingly, the 1992 measurement of Haniff et al. (1995), made in an almost identical bandpass to the 905-nm band used for these observations, is consistent with the diameter modulation seen during 1997–9 and therefore suggests that the variation in χ Cygni may be coherent over five cycles.

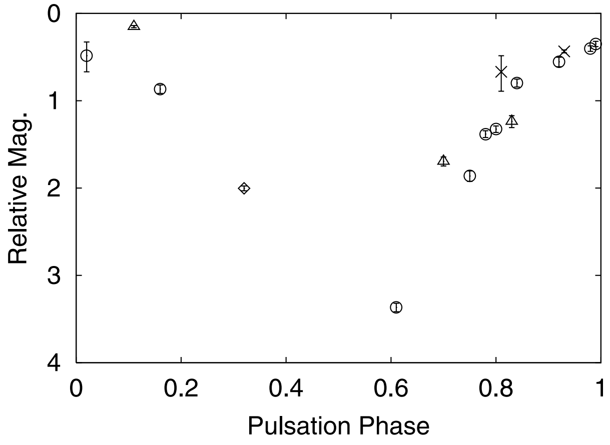

Figure 3. Light curve for χ Cygni at 905 nm. The detected flux relative to that of α Lyrae is plotted on a magnitude scale. The different symbols indicate cycle number, as in Fig. 2. The typical errors, as estimated from the scatter of repeated measurements, are 0.01–0.02 mag.

Despite much sparser coverage of the pulsation cycle at 1.3 μm, it is clear that the behaviour of the apparent diameter of χ Cygni in this waveband, shown in the lower panel of Fig. 2, is very different to that in the 905-nm band. For example, the ratio of the 1.3-μm diameter at maximum light to that three-quarters of a cycle later, in 1998, is slightly greater than unity, whereas the same ratio at 905 nm is 0.74 ± 0.02. Each 1.3-μm measurement is also smaller than the 905-nm diameter at the same phase. We have observed little change in the 1.3-μm diameter, but large variations with different phase-dependence to those at 905 nm cannot be ruled out.

As well as monitoring the diameter of the source, simultaneous 905-nm photometry of χ Cyg relative to α Lyr was also performed. This took advantage of the need for frequent calibrator observations of the star and capitalized on the ~20 arcsec photometric field of view of COAST. This was comfortably large enough to accept a seeing-limited image, while small enough to limit the effect of the lunar background. The errors on the estimates, based on the scatter of repeated measurements each night, were typically 0.01–0.02 mag. This photometry is presented in Fig. 3 and shows that the photometric variations were well correlated with the diameter variations measured in the same waveband.

3.2 Discussion

The large (~45 per cent) size changes seen in χ Cygni at 905 nm are consistent with the behaviour seen by B98 at 830 and 940 nm for R Leonis, with a relatively a slow diameter increase from maximum light to minimum light and then a rapid decrease in apparent size. This suggests that, at least in these passbands, large apparent diameter changes are the norm for oxygen-rich Miras such as these. The new 1.3-μm data presented here though show no such behaviour, and imply that we are not seeing the same photospheric layer (or combination of layers) in the two wavebands.

Hinkle, Hall & Ridgway (1982) measured the time-variation of the radial velocity from photospheric CO lines in χ Cygni, and by integration of their velocity curve, calculated that the displacement of the line-forming region over a pulsation cycle was 240 $R_{\odot}$, with maximum radius at phase 0.4. Adopting the *Hipparcos* (ESA 1997) distance to χ Cygni of 106 ± 15 pc, our measured angular size change implies a change in half-width-half-maximum of

$\sim$80 $R_\odot$ at 905 nm, with maximum size at phase 0.5. This discrepancy suggests that one or both of the apparent diameter and the CO line-forming region do not trace a single layer of gas throughout the pulsation cycle.

A zeroth-order analysis would predict mainly continuum emission from χ Cygni to be transmitted by our *J*-band filter. While the spectra of cool stars do have a wide absorption feature at 1.4 μm owing to H_2O, most of the photons in the wavelength range of the feature would be expected to be absorbed by telluric water and thus not detected. The fact that the observed 1.3-μm diameter of χ Cygni is always smaller than the 905-nm diameter at the same epoch undoubtedly supports this conclusion. Thus, if the 1.3-μm diameter at least approximately indicates the position of the continuum-forming photospheric layers, then some other mechanism must be responsible for the rapid decrease in apparent size between phases 0.7 and 0.8, which is seen at 905 nm but not at 1.3 μm.

One plausible explanation concerns the 905-nm bandpass used for the measurements reported here. This is similar to that of the 830- and 940-nm filters used by B98, in that while the transmitted flux is dominated by continuum emission, there is weak contamination by TiO absorption bands, whose strengths vary with pulsation phase (Spinrad & Wing 1969). Photons detected in this passband thus originate from several different layers within the stratified photosphere of the star, with their relative contributions varying with phase. Since an increase in the TiO band strength implies an increase in the opacity of the higher, cooler layers where the TiO molecules are found, this would be expected to artificially enlarge the apparent size of the star at these wavelengths.

Usefully, the strength of the TiO absorption bands in the spectrum of an M-type Mira can be used to define its spectral type. Though χ Cyg is classified as an S-type Mira, its ZrO bands are much weaker than those owing to TiO (Lockwood & Wing 1971). Thus an 'M-equivalent' spectral type can be assigned on the basis of the TiO (and VO for late spectral types) band strength. Narrow-band spectrophotometry by Lockwood & Wing (1971) shows that this spectral type is earliest close to visual maximum for χ Cyg. The spectral type increases until minimum light is reached, remaining constant at $\sim$M9 up to phase $\sim$0.7, after which it falls rapidly. The variation of spectral type index (Lockwood 1972), which is a direct measure of the strength of the TiO and VO bands, with pulsation phase, is shown in Fig. 4. This variation is well correlated with the diameter changes at 905 nm, and thus suggests that a substantial fraction of the apparent diameter variation at 905 nm is caused by changes in TiO opacity in the outer photospheric layers, and not by physical motions of the photosphere. The diameter measurements at 1.3 μm are more likely to trace continuum emission, and are consistent with much smaller variations, as would be expected in this scenario.

As well as being correlated with the changes in spectral type, the 905-nm diameter variations also trace the 905-nm light curve. The photometric amplitude in this band is 3.0 mag, which can be compared with the amplitude in the nearby 1.04-μm continuum band of only 2.3 mag. (Lockwood & Wing 1971). Most of the extra amplitude at 905 nm must thus arise from phase-coherent variations in TiO absorption in this band, consistent with our proposed mechanism for the apparent diameter variations at 905 nm. We therefore conclude that the large diameter changes seen in the 905-nm band are mostly caused by changes in the opacity owing to TiO and not by bulk motion of the stellar atmosphere.

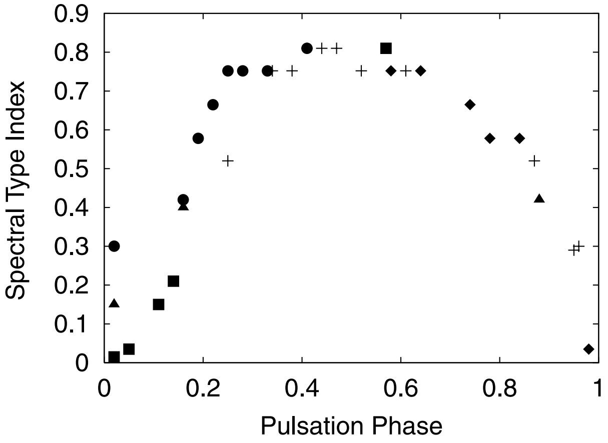

Figure 4. Variation of spectral type index with pulsation phase for χ Cygni. Spectral types were taken from Lockwood & Wing (1971), and converted back to spectral type index *D* (which provides a more direct measure of TiO and VO band-strengths) using the calibration given by Lockwood (1972). Crosses, discs, triangles, diamonds, and squares indicate measurements from the cycles commencing in 1965, 1966, 1967, 1968 and 1969 respectively.

We can compare our results with the predictions of the latest non-linear pulsational models for Mira variables. Hofmann, Scholz & Wood (1998) have calculated the apparent diameters of six model Mira variables covering a wide range of effective temperatures, at various wavelengths and phases in their pulsation cycles. The physical size of their model stars is largest at phase $\sim$0.2, therefore the apparent diameter in the continuum is larger at maximum than at minimum light for all six of the model series. At near-continuum wavelengths increased contamination by molecular bands tends to enlarge the star near minimum. However, despite this effect, five of the six model series still appear larger at maximum, the exception being the P series (mean $T_{\mathrm{eff}} = 2860$ K, fundamental-mode pulsation), whose apparent diameter at 820 nm and 920 nm is 15–30 per cent larger at minimum than at maximum. If we adopt the Hofmann et al. predictions for phase-dependent limb-darkening, then the apparent diameter changes expected for a Gaussian model fit should be slightly smaller than this.

These size differences are much smaller than the 45 per cent we have observed for χ Cygni at 905 nm, which suggests that either the treatment of molecular opacity in the models is inadequate, or the physical size of χ Cygni is indeed largest near minimum light. Clearly, further measurements are needed to assess the detailed reliability of these models, but even the current generation of ground-based interferometers are capable of providing useful diagnostic data. Given the precision now available with long-baseline interferometers ($\sim$1 per cent), further diameter measurements at 1.3 μm, or another uncontaminated waveband such as the 1.04-μm band, with better coverage of the pulsation cycle, should soon allow the phase-dependence of the continuum diameter to be determined reliably once and for all.

4 CONCLUSIONS

We have measured phase-coherent variations in the apparent diameter of χ Cygni over two consecutive variability cycles. The amplitude at a wavelength of 905 nm is 45 per cent of the smallest diameter. A small number of 1.3-μm diameter measurements suggest a much smaller amplitude in this waveband. The 905-nm results are inconsistent with the predictions of the latest pulsation models which typically show a much smaller amplitude of variation and larger apparent sizes at maximum than at minimum brightness.

We find the apparent diameter at 905 nm is well correlated with the strength of the TiO absorption bands in this region of the spectrum. We conclude that the large diameter changes at 905 nm are caused by phase-coherent variations in the opacity due to titanium oxide and not by bulk motions of the outer stellar atmosphere. Diameter monitoring at 1.3 μm with better coverage of the pulsation cycle is required to determine the amplitude of the photospheric pulsation, and the visual phase corresponding to the 'true' maximum size, but should be possible with existing interferometric arrays.

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