The angular diameter of R Doradus: a nearby Mira-like star

T. R. Bedding,1 A. A. Zijlstra,2 O. von der Lühe,2 J. G. Robertson,1 R. G. Marson,1,3 J. R. Barton4 and B. S. Carter5,6

1 School of Physics, University of Sydney 2006, Australia
2 European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching bei München, Germany
3 Current address: NRAO Array Operations Center, P.O. Box 296, Socorro NM 87801, USA
4 Anglo-Australian Observatory, P.O. Box 296, Epping 2121, Australia
5 South African Astronomical Observatory, P.O. Box 9, Observatory 7935, South Africa
6 Current address: Carter Observatory, P.O. Box 2909, Wellington, New Zealand

25 December 2021

ABSTRACT

We find the angular diameter of R Doradus to be 57 ± 5 mas, exceeding that of Betelgeuse and implying that R Dor is larger in apparent size than every star except the Sun. R Dor is shown to be closely related to the Mira variables. We estimate an effective temperature of 2740 ± 190 K, a distance of 61 ± 7 pc, a luminosity of 6500 ± 1400 $L_\odot$, and a radius of 370 ± 50 $R_\odot$. The characteristics of R Dor are consistent with it being near the edge of a Mira instability strip. We detect non-zero closure phases from R Dor, indicating an asymmetric brightness distribution. We also observed W Hya, a small-amplitude Mira, for which we find an angular diameter of 44 ± 4 mas.

Key words: techniques: interferometry – stars: imaging – stars: individual: R Dor – stars: individual: $\alpha$ Ori– stars: individual: W Hya – stars: AGB and post-AGB

1 INTRODUCTION

Several nearby red giant and supergiant stars have been resolved with 4-m telescopes, producing a number of significant results. Angular diameter measurements have provided evidence for first-overtone pulsation in Mira variables (Tuthill et al. 1994b; Haniff et al. 1995) and produced a new log $T_{\text{eff}}$ versus $(J - K)$ relation (Feast 1996). Also important are the discoveries of hotspots on $\alpha$ Ori (Betelgeuse) by (Buscher et al. 1990) and of asymmetries in the atmosphere of $\alpha$ Cet and similar stars (Wilson et al. 1992; Haniff et al. 1992; Tuthill et al. 1994a).

It has long been assumed that $\alpha$ Ori, a red supergiant, has the largest angular diameter of any star in the night sky. Here we report measurements of the red giant R Doradus (HR 1492), a semiregular variable of spectral type M8, which show it to exceed $\alpha$ Ori in angular size. Although the $V$ magnitude of R Dor is only 5.4, at infrared wavelengths it rivals $\alpha$ Ori as the brightest star in the sky. This has lead Wing (1971) to predict a large angular size but R Dor has not previously been observed at high angular resolution, presumably due to its southerly declination. We also report observations of W Hydrae (HD 120285), which is a small-amplitude Mira variable that also has a large angular diameter.

2 OBSERVATIONS

We have carried out observations of R Dor in the near infrared (1.25 $\mu$m) and the red (855 nm) using aperture-masking. This technique involves modifying the telescope pupil with a mask, the rationale for which has been discussed elsewhere (Haniff & Buscher 1992; Buscher & Haniff 1993; Bedding et al. 1993; Haniff 1994). In brief, an aperture mask with a small number of non-redundantly spaced holes provides more accurately calibrated measurements at the full diffraction limit. This comes at the expense of lower sensitivity and poorer spatial-frequency coverage, and a good compromise in the photon-rich infrared regime is to use an annular mask (Haniff & Buscher 1992). This has full spatial frequency coverage while being minimally redundant: roughly speaking, each baseline is measured twice. Furthermore, a thin annulus whose width is comparable to the atmospheric coherence length ($r_0$) largely retains the advantages of accurate calibration and enhanced resolution. To date, however, results from annular masks have only been published for binary stars (Haniff et al. 1989).

In the visible regime, where photon noise generally dominates over atmospheric noise, an annular mask is not a good choice. Instead, improved sensitivity and spatial-frequency coverage is best achieved by using a long slit (Aime & Roddier 1977; Buscher & Haniff 1993).

* E-mail: bedding@physics.usyd.edu.au
© 1996 RAS
2.1 NTT Observations

Observations with the 3.5-m New Technology Telescope (NTT) were made with the SHARP infrared camera (Hofmann et al. 1992). Details of the experimental setup are given in Bedding et al. (1993, 1995). We observed R Dor on 1993 August 7 using an aperture mask with seven holes arranged in a non-redundant two-dimensional configuration. Each hole had an effective diameter (as projected onto the primary mirror) of 25 cm and lay on a circle of diameter 3.05 m. The wavelength was 1.25 μm, selected using a standard J filter. For both R Dor and a calibrator star (γ Ret), we obtained 500 short (0.1 s) exposures.

Fringe visibilities were extracted from the averaged power spectrum and were calibrated for atmospheric and instrumental effects by dividing by visibilities from the calibrator star. The upper panel of Figure 1 shows these calibrated visibilities as a function of baseline length. It is clear that R Doradus is resolved, despite the fact that the visibility at this wavelength does not fall below 50%, even on the longest baselines. There is a scatter in the visibility measurements at fixed baselines whose cause is unclear, although it may be due to a mismatch in seeing conditions for observations of R Dor and its calibrator star. Fitting a uniform-disk model to these data gives a diameter of (57 ± 5) mas (milliarcsec).

Note that we expect the calibrator star γ Ret (HR 1264; V = 4.5; M4 III) to be slightly resolved. This star has no measured angular diameter, but Ochsenbein & Halbwachs (1982) estimate a diameter of 11 mas based on its spectral type. Using the V − K calibration of Di Benedetto (1993) gives 7.5 mas. Correcting the visibility curve of R Dor for the non-zero size of the calibrator star leads to a slight upwards revision in the diameter by 0.5–1 mas, depending on the actual diameter of γ Ret.

We also observed R Dor on 1993 August 6 using the J filter, this time with an annular mask that had an effective outer diameter of 3.3 m and a width of 20 cm (lower panel of Figure 1). Further observations using the same setup were obtained almost two years later, on 1995 July 19 (Figure 2). The former data set gave a uniform-disk diameter of (57 ± 5) mas and the latter gave (59 ± 3) mas, both in good agreement with the results from the 7-hole mask. The anomalous feature seen at short baselines in Figure 2 is due to miscalibration caused by slight differences in seeing between observations of the object and its calibrator star (Haniff & Buscher 1992). The effect is seen to lesser degrees in all of the plots presented here, and the affected data were excluded from the fits to the visibility function.

We observed W Hya with the annular mask on 1993 August 8. These observations used a variable filter (CVF) with a resolving power (λ/Δλ) of about 50, set to a wavelength of 1.45 μm. Two calibrator stars were used: HR 5192 and HR 5287. The result, shown in Figure 3, is a uniform-disk diameter of 44 ± 4 mas.
mounted on fixed rails at the coudé focus. The system differed from that described by Bedding et al. (1994), which consists of optical elements used the MAPPIT facility (Masked APerture-Plane Interference Telescope; Bedding et al. 1994), which consists of optical elements mounted on fixed rails at the coudé focus. The system differed in two important respects from that described by Bedding et al. Firstly, the wavelength-dispersed system was not used. Instead, the prism and cylindrical lens were replaced by an interference filter (λ = 855 nm, Δλ = 40 nm). Secondly, the detector was a CCD with on-chip binning, similar to the system used by Buscher et al. (1990).

For each observation we obtained 10 000 short (13 ms) exposures of the target followed by an identical number of the calibrator star. The aperture mask was a narrow slit whose effective width was 8 cm. The slit was aligned diametrically so that the maximum baseline corresponded to the full 3.89 m aperture of the AAT.

Figure 4. Visibilities of R Dor (three observations, upper panel) and α Ori (one observation, lower panel) measured at 855 nm with a slit mask on the AAT in 1995 January. For comparison, the dotted curves show the theoretical visibilities expected from uniform disks with diameters ranging from 50 mas (top) to 80 mas (bottom) in steps of 10 mas.

2.2 AAT Observations

On 1995 January 13 we observed R Dor and α Ori at 855 nm with a slit mask using the 3.9-m Anglo-Australian Telescope (AAT). We used the MAPPIT facility (Masked APerture-Plane Interference Telescope; Bedding et al. 1994), which consists of optical elements mounted on fixed rails at the coudé focus. The system differed in two important respects from that described by Bedding et al. Firstly, the wavelength-dispersed system was not used. Instead, the prism and cylindrical lens were replaced by an interference filter (λ = 855 nm, Δλ = 40 nm). Secondly, the detector was a CCD with on-chip binning, similar to the system used by Buscher et al. (1990).

For each observation we obtained 10 000 short (13 ms) exposures of the target followed by an identical number of the calibrator star. The calibrator for R Dor was again γ Ret, while for α Ori we used γ Ori. The aperture mask was a narrow slit whose effective width was 8 cm. The slit was aligned diametrically so that the maximum baseline corresponded to the full 3.89 m aperture of the AAT. The central 1.51 m was obscured by the secondary mirror, which results in a gap in spatial-frequency coverage: baselines having lengths between 1.19 m and 1.51 m are not sampled.

For R Dor we obtained two observations with the slit oriented at position angle 65° on the sky and a further observation at 145°. Figure 5 shows calibrated visibilities for these three observations, as well as for a single observation of α Ori obtained at position angle 115°. The visibilities of R Dor have been corrected for the non-zero angular size of the calibrator star, assumed to be 10 mas. This correction is only a few percent, even at the longest baselines. Note that fringe visibilities from α Ori are likely to be affected by the presence of surface features (Buscher et al. 1990; Wilson et al. 1992). However, our aim here is to establish that R Dor exceeds α Ori in angular size, which is demonstrated by our observations, at least at this wavelength. We should note that our measured angular diameters will be affected by limb darkening and the presence of hotspots and non-circularity, which may be different for the two stars. By calculating the bispectrum of each observation, we find that R Dor shows non-zero closure phases (Figure 5). These imply an asymmetrical brightness distribution similar to that previously found for the supergiant α Ori and Mira variables such as α Cet (Wilson et al. 1992; Haniff et al. 1992; Tuthill et al. 1994a). R Dor is the first non-Mira giant from which non-zero closure phases have been detected. Note that Di Benedetto & Bonneau (1990) found anomalously high visibilities on long baselines for the star β And (M0 III) which may indicate surface structure, but those measurements did not provide phase information.

The limited position-angle coverage of our data prevents image reconstruction and R Dor is clearly a good candidate for more detailed observations, particularly in view of its large angular size.

3 DISCUSSION

3.1 Angular diameter

To obtain the true photospheric angular diameter of an M-star from a measured diameter requires two corrections, both of which are strongly dependent on wavelength. The first correction is for limb darkening, which makes a star appear smaller. The second correction is for opacity effects from deep molecular absorption bands, in which the star appears larger. This latter effect explains why the angular size at 855 nm is larger than at J band: the 855 nm filter (with 40 nm bandpass) contains a strong TiO absorption feature whose depth is about 50% of the continuum (see Fig. 9 of Bessell et al. 1989).

In the near infrared both effects are greatly reduced and the measured diameter is within 1–2% of the ‘true’ stellar diameter (Bessell et al. 1989, 1996), where the latter is defined by the point at which the Rosseland optical depth is unity. We therefore adopt our measurement of R Dor at 1.25 μm (57 ± 5 mas) as the true angular diameter, to be used in the next section.

Measurements at visible wavelengths can be corrected for limb-darkening and opacity effects, although this correction is somewhat ad hoc due to the lack of reliable model atmospheres. Haniff et al. (1995) made these corrections to their observations of W Hya, which were obtained with a slit mask on the WHT at wavelengths of 700 and 710 nm. They arrived at a photospheric diameter of 46 ± 6 mas (after corrections of 30–40%). This result agrees with our 1.45 μm measurement of 44 ± 4 mas, giving support to the accuracy of their correction process.

For comparison, the uniform-disk diameter of α Ori at 2.2 μm has been measured to be 44 mas (Dyck et al. 1992). Thus, while R Dor is the largest star in the sky, W Hya rivals α Ori for second place.
3.2 Bolometric magnitude and effective temperature

The effective temperature of a star can be determined from its angular diameter $\phi$ and its apparent flux (Ridgway et al. 1980; Bessell et al. 1989):

$$\log(T_{\text{eff}}/K) = 4.22 - 0.1m_{\text{bol}} - 0.5 \log(\phi/\text{mas}),$$

where $m_{\text{bol}}$ is the bolometric magnitude.

Several infrared magnitude determinations for R Dor are available in the literature (Neugebauer et al. 1971; Kerschbaum & Hron 1994), which we have converted to the Carter system (Carter 1990; McGregor 1994). These are supplemented by several new observations made using the 0.75-m telescope and the MKII Infrared Photometer at Sutherland Observatory, South Africa. To allow observation of such a bright star, an aperture mask was placed over the telescope for some of the observations. The accuracy of these measurements is about 0.03 magnitudes at $JHK$ and 0.05 at $L$ on the Carter system.

We derive the following average magnitudes: $J = -2.51$, $H = -3.50$, $K = -3.91$ and $L = -4.30$. The scatter between measurements at different epochs is about 0.1 to 0.2 magnitudes, with an uncertainty of at least 0.03 magnitude. We note, however, that the accuracy of Hipparcos parallaxes for these stars may be compromised by time-varying surface features which, for the closest objects, may affect the centroid at a level of a few mas.

We also observed R Dor in two bands at Sutherland on 1993 August 7, contemporaneously with our infrared diameter measurement. We obtained $J = -2.59$ and $L = -4.37$, implying that R Dor was about 0.07 magnitudes brighter than the average values given above. On this basis, we take the bolometric magnitude at the epoch of our diameter measurement to be $-0.96$, which yields an effective temperature of 2740±190 K. This is somewhat higher than previous indirect estimates: Neugebauer et al. (1971) gave 2400 K, de Jager et al. (1988) gave 2365 K (after correcting for an obvious misprint) and Judge & Stencel (1991) gave 2230 K.

The differences may be due to the inadequacies of the indirect methods used to estimate temperatures from colour of such red stars, and also to the intrinsic variability of R Dor.

3.3 Classification, distance and radius

R Dor is an M8 giant and the brightest, and presumably closest, star with such a late spectral type (Wing 1971). The late spectral type makes it likely that R Dor lies on the asymptotic giant branch (AGB) rather than the red giant branch. The star is catalogued by Kholopov et al. (1988) as a semiregular variable of type SRb with a period of 338 days. Despite this classification as semiregular, R Dor is in many ways closer to the Miras than to other SRb stars. Its period is near the peak of the Mira period distribution function (250–350 days), while SRb stars almost always have much shorter periods (e.g., Kerschbaum & Hron 1992; Jura & Kleinmann 1992b).

Further evidence for the Mira-like nature of R Dor comes from evidence for mass loss, which is commonly seen in Miras with periods of more than 300 days (Jura & Kleinmann 1992a). In R Dor, evidence for mass loss comes from the 12-micron IRAS flux, which exceeds the ground-based N-band flux by a factor of two, indicating that there may be extended emission. There may also be an extended component at 60 and 100 micron, as claimed by Young et al. (1993).

Assuming that R Dor is closely related to the Mira variables, as seems likely from the preceding discussion, we can apply the period–luminosity relations for Miras in the LMC given by Feast (1996). For this we use the average magnitudes obtained above. We obtain a luminosity for R Dor of $6500 ± 1400 L_\odot$ and a distance of $61 ± 7$ pc, with the result being the same whether we use the period–bolometric magnitude or the period–$K$-magnitude relation.

The uncertainty is based on the scatter in the observed period–luminosity relation and the uncertainty in the distance to the LMC. Our distance for R Dor agrees with estimates of 60 pc by Judge & Stencel (1991) and 51 pc by Celis (1995).

Comparison with the Hipparcos distance will soon be possible. Being one of the few red giants accessible to Hipparcos, probably closer than $\alpha$ Cet, R Dor will be valuable in establishing the zero-point of the Mira period–luminosity relation. We note, however, that the accuracy of Hipparcos parallaxes for these stars may be compromised by time-varying surface features which, for the closest objects, may affect the centroid at a level of a few mas.

This distance together with our observed angular diameter implies a stellar radius of $370 ± 50 R_\odot$. From the pulsation equation $Q = P(M/M_\odot)^{1/2}(R/R_\odot)^{-3/2}$ and assuming $Q = 0.04$ days (appropriate for first overtone pulsation), we derive a mass of $0.7 ± 0.3 M_\odot$. All the derived parameters are consistent with a classification of this star as Mira-like, with the effective temperature being slightly higher than the average for Miras (Haniff et al. 1995; Feast 1996).

Although angular diameter measurements of Miras have favoured first overtone pulsation (Tuthill et al. 1994b; Haniff et al. 1995), there is recent evidence from cluster long-period variables in the LMC that the dominant mode is the fundamental (Wood & Sebo 1996). If we assume that R Dor pulsates in the fundamental mode, which means adopting a value of $Q = 0.09$ days (Fox & Wood 1982), we obtain a mass of $3.5 ± 1 M_\odot$. This is higher than expected from its period (Feast 1989; Vassiliadis & Wood 1993), giving further support to first-overtone pulsation.

All previous measurements of the radii of Miras fall in the range 400–500 $R_\odot$, which is taken by Haniff et al. (1995) as evidence that Miras are associated with a well-defined instability strip. The fact that R Dor shows a more irregular pulsation behaviour but with many characteristics of a Mira is consistent with it lying near the edge of such a strip.

ACKNOWLEDGMENTS

We thank the staff at the AAT and NTT for their assistance. We also thank Reiner Hofmann for making the SHARP fore-optics, Gerardo Iile and the staff in the La Silla workshop for making the NTT masks, SHARP experts Lowell Tacconi-Garman and Andreas Eckart for excellent support during the observations and Andreas Quirrenbach for making NTT time available in 1995 for observations of R Dor. We are grateful to Dave Laney, Freddy Marang and Patricia Whitelock for obtaining photometry at SAAO and we thank Mike Bessell and Lawrence Cran for useful discussions. We also thank the referee, Chris Haniff, for many valuable suggestions. The development of MAPPIT was supported by a grant under the CSIRO Collaborative Program in Information Technology, and by
funds from the University of Sydney Research Grants Scheme and the Australian Research Council.

REFERENCES

Aime C., Roddier F., 1977, Opt. Commun., 21, 435
Bedding T. R., von der Lühe O., Zijlstra A. A., Eckart A., Tacconi-Garman L. E., 1993, ESO Messenger, 74, 2
Bedding T. R., Robertson J. G., Marson R. G., 1994, A&A, 290, 340
Bedding T. R., von der Lühe O., Zijlstra A. A., 1995, in Walsh J., Danziger I. J. (eds.), Science with the VLT, p. 100, ESO Springer: Berlin
Bessell M. S., Brett J. M., Scholz M., Wood P. R., 1989, A&A, 213, 209
Bessell M. S., Scholz M., Wood P. R., 1996, A&A, 307, 481
Buscher D. F., Haniff C. A., 1993, J. Opt. Soc. Am. A, 10, 1882
Buscher D. F., Haniff C. A., Baldwin J. E., Warner P. J., 1990, MNRAS, 245, 7p
Carter B. S., 1990, MNRAS, 242, 1
Celis S. L., 1995, ApJS, 98, 701
de Jager C., Nieuwenhuijzen H., van der Hucht K. A., 1988, A&AS, 72, 259
Di Benedetto G. P., 1993, A&A, 270, 315
Di Benedetto G. P., Bonneau D., 1990, ApJ, 358, 617
Dyck H. M., Benson J. A., Ridgway S. T., Dixon D. J., 1992, AJ, 104, 1982
Feast M. W., 1989, In: Schmidt, E. (ed.), IAU Colloquium 111: The use of pulsating stars in fundamental problems of astronomy, pp. 205–213, Cambridge University Press, Cambridge and New York
Feast M. W., 1996, MNRAS, 278, 11
Fox M. W., Wood P. R., 1982, ApJ, 259, 198
Haniff C. A., 1994, in Robertson J. G., Tango W. J. (eds.), IAU Symposium 158: Very High Angular Resolution Imaging, p. 317, Kluwer: Dordrecht
Haniff C. A., Buscher D. F., 1992, J. Opt. Soc. Am. A, 9, 203
Haniff C. A., Buscher D. F., Christou J. C., Ridgway S. T., 1989, MNRAS, 241, 51p
Haniff C. A., Ghez A. M., Gorham P. W., Kulkarni S. R., Matthews K., Neugebauer G., 1992, AJ, 103, 1662
Haniff C. A., Scholz M., Tuthill P. G., 1995, MNRAS, 276, 640
Hofmann R., Bletz M., Duhoux P., Eckart A., Krabbe A., Rotaciuc V., 1992, in Ulrich M.-H. (ed.), Progress in Telescope and Instrumentation Technologies, p. 617, ESO: Garching
Judge P. G., Stencel R. E., 1991, ApJ, 371, 357
Jura M., Kleinmann S. G., 1992a, ApJS, 79, 105
Jura M., Kleinmann S. G., 1992b, ApJS, 83, 329
Kersbaaum F., Horon J., 1992, A&A, 263, 97
Kersbaaum F., Horon J., 1994, A&AS, 106, 397
Kholopov P. N., et al., 1988, General Catalogue of Variable Stars, 4th Edition, Bull. Inf. Centre Donnees Stellaires
McGregor P. J., 1994, PASP, 106, 508
Neugebauer G., Sargent W. L. W., Westphal J. A., Porter F. C., 1971, PASP, 83, 305
Ochsenbein F., Hallwachs J. L., 1982, A&AS, 47, 523
Ridgway S. T., Joyce R. R., White N. M., Wing R. F., 1980, ApJ, 235, 126
Tuthill P. G., Haniff C. A., Baldwin J. E., 1994a, in Robertson J. G., Tango W. J. (eds.), IAU Symposium 158: Very High Angular Resolution Imaging, p. 395, Kluwer: Dordrecht
Tuthill P. G., Haniff C. A., Baldwin J. E., Feast M. W., 1994b, MNRAS, 266, 745
Vassiladis E., Wood P. R., 1993, ApJ, 413, 641
Volk K., Cohen M., 1989, AJ, 98, 931
Wilson R. W., Baldwin J. E., Buscher D. F., Warner P. J., 1992, MNRAS, 257, 369
Wing R. F., 1971, PASP, 83, 301
Wood P. R., Sebo K. M., 1996, MNRAS, 282, 958
Young K., Phillips T. G., Knapp G. R., 1993, ApJ, 409, 725
This paper has been produced using the Royal Astronomical Society/Blackwell Science \LaTeX{} style file.
Figure 5. Bispectra from observations of R Dor (lower) and the calibrator $\gamma$ Ret (upper) using a slit mask on the AAT. The amplitude and phase of the complex bispectrum at each point are represented by intensity and colour, respectively, with blue corresponding to zero closure phase. The axes are spatial frequencies along the slit ($u_1$ and $u_2$), so that each point in the plane defines a triangle of spatial frequencies ($u_1$, $u_2$ and $u_1 + u_2$). Only the nondegenerate portion of the bispectrum is shown here, which is contained in a triangle bounded by the lines $u_1 = 0$, $u_1 = u_2$ and $u_1 + u_2 = u_{\text{max}}$, where $u_{\text{max}}$ is the maximum spatial frequency sampled by the slit (see Buscher & Haniff 1993). The green region in the bispectrum of R Dor at long baselines (high spatial frequencies) indicates non-zero closure phases.