ANGULAR SIZE MEASUREMENTS OF CARBON MIRAS AND S-TYPE STARS

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ABSTRACT

In our continuing investigation of highly evolved stars, we report new interferometric angular diameter observations of 5 carbon and 4 S-type Mira variable stars, and 4 non-Mira S stars. From the data, effective temperatures and linear radii are calculated. We compare the values of these parameters obtained for stars discussed in this paper with the same parameters for oxygen-rich giants/supergiants, oxygen-rich Mira variables, and non-Mira carbon stars presented in Dyck et al. (1996a, AJ, 111, 1705), van Belle et al. (1996, AJ, 112, 2147), and Dyck et al. (1996b, AJ, 112, 294), respectively. There are two principal findings from a synthesis of these studies. First, the non-Mira variables of each chemical class are consistently hotter and smaller than their Mira-variable counterparts. Second, the S stars lie between the oxygen-rich and the carbon-rich stars in both effective temperature and linear radius, for both the Mira-type and non-Mira stars.

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1. INTRODUCTION

Using the Infrared Optical Telescope Array (IOTA, see Carleton et al. 1994 and Dyck et al. 1995) we have been carrying out a program of interferometric high-resolution observations of highly evolved stars. In previous papers (van Belle et al. 1996; Dyck et al. 1996a, Dyck et al. 1996b) we detail the results from IOTA of oxygen-rich Mira variables, giant/supergiant stars and carbon stars; in this paper we shall discuss interferometric observations of carbon Miras, and S-type Miras and non-Miras and compare them to our previous results. Using previously compiled stellar catalogs (e.g., Khlopov et al. 1988; Gezari et al. 1993), observed fluxes and estimates of surface temperatures allowed us to estimate blackbody angular diameters for these stars; more than a dozen carbon Mira variables and two dozen S-type stars (both Miras and non-Miras) have angular diameters in excess of 5 milliarcseconds (mas), easily resolvable by IOTA. Although this is in contrast to the 70+ oxygen-rich Mira variables and the few hundred oxygen-rich giants/supergiants stars in excess of IOTA’s resolution limit, this is still enough of a sample to begin characterizing the differences between the oxygen-rich, S-type, and carbon stars. Presented in this paper are angular sizes for 5 carbon Miras and 4 S-type Miras, in addition to angular sizes for 4 out of 7 non-Mira S-type stars observed (the latter three being observed but unresolved), along with analyses comparing Mira variable and non-Mira stars of the three abundance types.

S stars exhibit an envelope enriched in carbon and heavy elements, indicative of the s-process (Smith & Lambert 1990). Optical surveys of stars have turned up few of these stars; e.g., the Bright Star Catalog (Hoffleit & Jaschek 1982) has only ≈0.1% S-type stars (Jura 1988). Infrared studies are more successful; e.g., the Two Micron Sky Survey (Neugebauer & Leighton 1969, henceforth TMSS) has proportionately an order of magnitude more stars, indicating the cooler nature of these stars. The TMSS indicates roughly a 3:1 ratio of carbon stars to S stars (Wing & Yorka 1977). Two classes of S stars are thought to exist, as suggested by Iben & Renzini (1983) and subsequently supported by a number of observational studies. Extrinsic S stars includes stars with altered elemental abundances, through the mechanism of mass transfer from a companion (e.g., Jorissen & Mayor 1992). Intrinsic S stars are thought to be high luminosity stars lying upon the AGB (e.g., Little et al. 1987; Smith & Lambert 1988). The presence of technetium in the spectra of S stars

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allows for the differentiation of the two classes; intrinsic S stars exhibit $T_c$, while in extrinsic S stars $T_c$ is absent. ($T_c$ is an $s$-process element with no stable isotope; its presence in a spectrum is a sign of recent convective mixing within an extrinsic S star.) The S stars addressed in this paper are all intrinsic S stars.

The evolutionary status of the S stars has been thought to be intermediate between the oxygen-rich and the carbon-rich stars (Iben & Renzini 1983). This hypothesis is supported by observation that S stars bridge an abundance gap between oxygen-rich and carbon stars, being within 1.05 of $[O]=-[C]$ (Scalo & Ross 1976). This interpretation, however, has been called into question with the discovery of carbon stars with $60 \mu m$ excesses (Willems & de Jong 1986; Thronson et al. 1987), and oxygen-rich circumstellar shells (Little-Marenin 1986; Willems & de Jong 1986). A lively debate on the nature of this aspect of stellar evolution has ensued (cf. de Jong 1989, Zuckerman & Maddalena 1989). In analysis of these observations, it has been suggested (e.g., Willems & de Jong 1986, 1988; Chun & Kwok 1988; Kwok & Chun 1993) that the M to C transition occurs on very short timescales ($<100$ yr), with mass loss ceasing during the transition from O-rich to C-rich surface abundances. In contrast to these conclusions, Jura (1988), using $TMSS$ and $IRAS$ data, and Bieging & Latt (1994), using millimeter CO emission data, both infer continuing mass loss over much longer time scales ($10^4$ yr).

Independent of how stars become carbon stars, there is common agreement that these objects represent evolutionary ones on the AGB (cf. Groenewegen et al. 1992; Zuckerman et al. 1978). A great deal of mass loss is associated with carbon stars, as inferred from $IRAS$ data (e.g., Claassen et al. 1987; Jura 1988) and CO emission data (e.g., Knapp & Morris 1985). For non-Mira carbon stars, as investigated in one of our previous papers (Dyck et al. 1996b), the mean temperature was measured to be $3000 \pm 200$ K, the mean radius was estimated to be $400 R_\odot$, making them more comparable to oxygen-rich Miras than to giant and supergiant stars. Two of the carbon stars (S Aur and CIT 13) were found to have significant effects of circumstellar shells on their temperature determinations.

2. OBSERVATIONS

The data reported in this paper were obtained in the $K$ band ($\lambda=2.2 \mu m$, $\Delta \lambda=0.4 \mu m$) at IOTA, using the telescopes at the [15 m, 15 m], [35 m, 5 m], and [35 m, 15 m] stations, providing 21 m, 35 m, and 38 m as nominal maximum baselines, respectively. Use of IOTA at $2.2 \mu m$ to observe evolved red stars offers three advantages: First, effects of interstellar reddening are reduced, relative to the visible ($A_K=0.1A_V$; see Mathis 1990); second, the effects of circumstellar emission and scattering are minimized in the near infrared (Rowan-Robinson & Harris 1983a); and, third, the $K$ band apparent uniform-disk diameter of Mira variables is expected to be close to the Rosseland mean photospheric diameter (see the discussion in Sec. 3). The interferometer, detectors and general data reduction procedures are described more fully in Carleton et al. (1994) and Dyck et al. (1995), with procedures relating specifically to Mira variables in van Belle et al. (1996). As was previously reported in these papers, starlight collected by the two 0.45 m telescopes is combined on a beam splitter and detected by two single element InSb detectors, resulting in two complementary interference signals. The optical path delay is mechanically driven through the white light fringe position to produce an interferogram with fringes at a frequency of 100 Hz. Subsequent data processing locates the fringes in the raw data and filters out the low- and high-frequency noise with a square filter 50 Hz in width.

Observations of target objects are alternated with observations of unresolved calibration sources to characterize slight changes in interferometer response, due to both seeing and instrumental variations. Calibration sources were selected from $V$ band data available in The Bright Star Catalog, 4th Revised Edition (Hoffleit & Jaschek 1982) and $K$ band data in the Catalog of Infrared Observations (Gezari et al. 1993), based upon angular sizes calculated from estimates of bolometric flux and effective temperature; calibration source visibility was selected to be at least 90% and ideally greater than 95%, limiting the effect of errors in calibrator visibility to a level substantially below measurement error.

Five carbon and four S-type Mira variable stars were resolved at IOTA during five observing runs between 1995 June and 1996 June; in addition, four non-Mira S-type stars, out of a total of seven observed, were resolved. The visibility data for the two detector channels have been averaged and are listed in Table 1, along with the date of the observation, the interferometer projected baseline, the stellar phase and the derived uniform disk angular size. Our experience with the IOTA interferometer (Dyck et al. 1996a) has demonstrated that the night-to-night rms fluctuations in visibility data generally exceed the weighted statistical error from each set of interferograms; we have characterized these fluctuations and use the empirical formula $\sigma_V=\pm 0.0509/\sqrt{\text{number of nights}}$ to assign the "external" error. The interested reader should see Dyck et al. (1996a) for a more complete discussion. Finally, visibility data were fit to uniform disk models to obtain an initial angular size $\theta_{\text{ID}}$. These uniform disk diameters and their estimated errors, derived from the uncertainty in the visibilities, are also listed in Table 1. Note that visibility observations spanning a small range of dates are averaged to obtain a single angular diameter but that observations separated by many months are averaged into independent diameters.

Typically, visibility points at a single telescope spacing, corresponding to a small range of projected interferometer baselines, were utilized in calculating the uniform disk diameter $\theta_{\text{ID}}$. For the stars in our sample, the visibility data were all at spatial frequencies, $x$, shortward of the first zero of the uniform disk model, $[2J_1(x)/x]$. Haniff et al. (1995) noted that the uniform disk model was not a particularly good model for visible-light data for Mira variables; rather, the data were a better fit to a simple Gaussian. Although we do not currently have multiple spatial frequency data for any Mira variables, we expect that the departures from a uniform disk model will not be as great at $2.2 \mu m$ as it is at visible
<table>
<thead>
<tr>
<th>Star</th>
<th>Date</th>
<th>$\theta$</th>
<th>$S_0$ (mas)</th>
<th>Visibility</th>
<th>$O_0$ (mas)</th>
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<td>S GEP</td>
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<td>0.22</td>
<td>27.32</td>
<td>23.677</td>
<td>1.967</td>
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<td>V CBH</td>
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<td>36.40</td>
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3. EFFECTIVE TEMPERATURES

Rough light-curve phases were initially established from data contained within The General Catalog of Variable Stars, 4th Edition (Kholopov et al. 1988, GCVS) and then refined from recent visual brightness data available from the Association Francaise des Observateurs d’Etoiles Variables (AFOEV) (Schweitzer 1996). See Paper I for details. Spectral types were taken from the GCVS and, therefore, represent only rough values. The stellar effective temperature, $T_{\text{eff}}$, is defined in terms of the star’s luminosity and radius by $L = 4\pi R^2 T_{\text{eff}}^4$. Rewriting this equation in terms of angular diameter $\theta$ and bolometric flux $F_T^{\text{bol}}$ a value of $T_{\text{eff}}$ was calculated from the flux and Rosseland diameter using $T_{\text{eff}} = 2341(F_T^{\text{bol}}/\theta_3^{1/4})$, the units of $F_T^{\text{bol}}$ are $10^{-8}$ erg cm$^{-2}$ s$^{-1}$, and $\theta$ is in mas. The error in $T_{\text{eff}}$ is calculated from the usual propagation of errors.

As in Paper I, we have used the model atmospheres of Scholz & Takeda (1987) to evaluate the effects of limb darkening, adopting (as they do) the surface where the Rosseland mean optical depth equals unity as the appropriate surface for computing an effective temperature. Although Scholz & Takeda’s models do not address carbon or S-type stars directly, we shall use them as sufficient approximations of the marginal effect of limb darkening at this wavelength. Following the treatment of Paper I, we have adopted, for the Mira-type variables, a multiplicative factor relating the Rosseland angular size to the uniform disk angular size: $\theta = 1.045 \theta_{\text{RS}}$, assumed to be independent of phase for this discussion. For the non-Mira stars, we use a correction of 1.022 rather than 1.045, following Dyck et al. (1996a, 1996b).

Another potential source of error for the angular size measurements of the greatly extended Mira variable stars is departures from spherical symmetry. We have a small amount of unpublished data on S CrB that indicates the potential for variation in angular size (12.2 – 13.7 mas) over a range of projected baseline angles ($\Delta\theta = 10^\circ$). Further observations are needed to be certain that the observations cannot be explained by another physical effect, although Tuthill (1994) has noted the same departure from spherical symmetry at shorter wavelengths. For the purpose of assigning an error, we assume an uncertainty of 15% in the angular sizes of Mira variables, based upon our observations of S CrB. This uncertainty has been added in quadrature to other sources of error. Similar observations for non-Mira stars (γ Leo, RS Cnc) give no indication of departure from spherical symmetry.

To compute the stellar bolometric flux for these stars, we have made use of data from a number of sources. We have taken the IOTA measurements of incoherent $K$ band fluxes that were obtained during each interferometric scan (see Pa-
per I for details). Contemporaneous V band measurements were obtained from the available AFOEV visual data for the variable stars (Schwitzer 1996). Non-contemporaneous data at L were taken from Gezari et al. (1993), and at 12.25, and 60 μm from the IRAS Point Source Catalog (IPAC 1986). The photometry for each source is listed in Table 2.

For the carbon stars in the sample, estimates of the K band reddening were taken from Claussen et al. (1987): A_V was estimated from A_K using the relation A_K = 0.11A_V from Mathis (1990). Reddening data were not readily available for the S stars and were not considered. However, since both types of objects are at roughly the same distances, we expect that reddening would be on the same order of magnitude as A_V and A_K for the carbon stars; since the K band photometry had the greatest effect on the computed F_TOT, with A_K of marginal effect on m_K (A_K≤0.06), we do not expect this to be significant. Nevertheless, we have included reddening consideration for completeness with the carbon stars, and will include lack of compensation for this effect in our estimation of error in F_TOT for the S-type stars.

Once the fluxes between 0.55 and 60 μm had been established, a Planck curve was fit to the data by means of a χ² minimization, and the bolometric flux calculated from a numeric integration of that curve. We note that such a curve is a poor fit, particularly at the longer wavelengths; however, the majority of the bolometric flux is contributed about the K band, the wavelengths of which (V, K, L bands) held the majority of the error in the fit.

Error in the estimation of F_TOT was calculated from a number of potential sources: K, V, L band photometry errors, long wavelength excess, and for the S-type stars, lack of reddening correction. We estimated Δm_V = ±1.0 mag for the V band data from the AFOEV archive. The error L band data, Δm_L = ±0.25 mag, was estimated from the reported variations in Gezari et al. (1993). Long wavelength excesses were found to contribute a negligible error to the estimate of F_TOT. Given the reddening for the carbon stars found in Claussen et al. (1987), an average reddening of A_K = ±0.06 was adopted as an additional source of error for the S-type stars. Errors in the estimation of F_TOT were added in quadrature to obtain a final F_TOT error value.

4. LINEAR RADIUS

Determination of linear radii from angular sizes requires an estimate of distances to these stars. A variety of indirect methods exist in the literature, exhibiting agreement within our sample at the 20% level, which is consistent with the spread in values of the previous investigation of a similar nature by Claussen et al. (1987). Where possible, we attempted to utilize two or more independent estimates of the stellar distances in order to assess the errors in these indirectly determined values; the values found can be found listed in Table 3. For the carbon Miras, Rowan-Robinson & Harris (1983b) estimated distances from the luminosities calculated by Cohen (1979) as a function of temperature index. Claussen et al. (1987) calculated the distances to these stars using the assumption M_K = −8.1, an assumption we also employed in estimating distance moduli. For our data, where more than one measurement of m_K was available, an average m_K was taken as a reasonable estimate for computation of the distance modulus. For the S Miras, Rowan-Robinson & Harris (1983a) adopted estimates of the luminosities for distance determination. For these stars Jura (1988) also assumed M_K = −8.1; again we have adopted this value and a weighted averaged for m_K (in the presence of more than one measurement) to obtain a distance estimate. Finally, for both Miras and non-Mira S/stars, Yorka & Wing (1977) suggest that maximum light M_V = −1.6 and I, respectively. Maximum light M_V's were obtained from the AFOEV visual light curves discussed earlier. Since reddening was not measured or estimated for these stars, we have assumed an average A_V=0.5, identical to the A_V's calculated for the carbon stars. Also, as pointed out to us by the referee, the expected evolution of M stars to S and then C stars would be accompanied by an increase in luminosity; assumptions of constant absolute K magnitude are inconsistent with that expectation.
indicating a conflict in the assumptions of Claussen et al. (1987) and Jura (1988). We expect that our use of other distance indicators along with these two will minimize any effect this conflict might have on our results.

As an estimate of the error in these distances, we compared the different distance values obtained for individual stars, where more than one value was available. The average standard deviation of the distances was 17%; hence, we have adopted a conservative 20% error as a reasonable uncertainty in the determined distances, noting that this consistent with typical errors in estimated distances to these objects (e.g., Celis 1980; Wyatt & Cahn 1983; Claussen et al. 1987; Feast et al. 1989). We note that the distances determined from the Yorka & Wing (1979) $M_V$ assumption change by only roughly 1/3 of an error estimate with the change in $M_V$ due to the assumed reddening of $A_V = 0.5$.

In addition to these methods of indirectly inferring distances, the direct measure of parallaxes to these stars became available after the initial submission of this paper with the release of the Hipparcos catalog (ESA 1997). Many of the parallaxes to these stars had considerable error bars attached to them; in fact, none of the S-type Mira variables had Hipparcos distances. The large angular size of these stars most likely made detection of parallax difficult; the scale of the parallax effect is roughly three to six times smaller than the angular sizes for these stars. As such, the Hipparcos distances have been included, but combined in quadrature to the indirect distance estimators.

We note that three S stars were unresolved by IOTA. The most distant S star resolved by the interferometer is AA Cyg at 759 pc; the distance of AD Cyg is inferred to be 1047 pc and unsurprisingly was not resolved. HR 8062 and IRC +40458, however, are indicated to be at distances of 274 and 459 pc, respectively. Using the average non-S-type Mira S radius of 298 $R_\odot$, these objects should be 10 and 6 mas in angular diameter, resolvable by IOTA. Subtracting a single standard deviation in radius results in IRC+40458 potentially being unresolved; however, HR 8062 should still have been resolved by IOTA. Hence, we suspect that our distance estimate to HR 8062 is in error.

5. A COMPARISON OF PARAMETERS

5.1 Temperature

In order to compare classes of stars, mean values and errors of the mean were computed, weighted by the individual standard deviations, where the data were taken from the present paper, Paper I or Dyck et al. (1996a, 1996b). The non-Mira oxygen-rich star mean temperature was computed from the giant stars later than spectral class M4 found in Dyck et al. (1996a), with the expectation that these objects were the closest analogs to the oxygen-rich Miras, which tend to be of the later M spectral types. The non-Mira carbon star mean temperature excludes the three lowest temperature points (S Aur, TW Oph, CIT 13), which are most likely either temperatures significantly affected by the presence of circumstellar shells (S Aur, CIT 13) or interstellar reddening (TW Oph) (see Dyck et al. 1996b for a discussion of both effects). The resultant values are listed in Table 4, along with the reference to the source of data.

There is a tendency for the effective temperature to decrease in progression from oxygen-rich to S-type to carbon; this is true for both Mira variables and non-Miras. The difference is $\Delta T_{Eff}=225$ K between the oxygen-rich and S-type stars, while $\Delta T_{Eff}=200$ K between the S-type and carbon stars. The total range in the two variable classes (Mira and non-Mira) is approximately 400 K, which is consistent for both sets. We believe the variation is real. Second, there is a difference $\Delta T_{Eff}=650$ K between the Mira and non-Mira stars of all three chemistry types, with the Miras being the cooler stars.

5.2 Size

Just as there is a progressive decrease in effective temperature among the types, there is a corresponding progres-
sive increase in linear radius from oxygen-rich to S-type to carbon. As with the temperatures, an average $R$ was computed for each subset with the error $\sigma_R$ being taken from the standard deviation of the radii in the subset. We note that the non-Mira oxygen-rich radius was estimated from Dyck et al.'s (1996a) M4 estimate and from the suggestion that a factor of 2 in size resulted from every decrease of 500 K in effective temperature; the resulting size of 160 $R_\odot$ is consistent with a spectral type of M7–M8, this estimate being reasonable to approximate the late spectral-type oxygen-rich Mira variable stars. For both Mira and non-Mira stars, there is a difference of approximately $\Delta R = 110-160R_\odot$ between the oxygen-rich and S-type stars, while $\Delta R$ is roughly 35–130 $R_\odot$ between the S-type and carbon stars; the increase in size is toward those stars that are believed to be more evolved. The smallest change (35 $R_\odot$) is between the S-type and carbon Miras, whose mean radius measurements have the largest error bars; the actual difference between these two subcategories could be masked by the large errors in distance to these objects. Between the Mira and non-Mira stars of all three chemistry types, there is also a $\Delta R$ of approximately 160–260 $R_\odot$ between types, with the Miras being larger.

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