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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. © *1997 American Astronomical Society.* [S0004-6256(97)03211-1]

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, 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., Kholopov *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 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 giant/supergiant 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 Tc, while in extrinsic S stars Tc is absent. (Tc is an *s*-process element with no stable isotope; its presence in a spectrum is a sign of recent convective mixing within an intrinsic 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 μm 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; Chan & Kwok 1988; Kwok & Chan 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 & Latter (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 stars evolving 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., Claussen *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±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 (λ=2.2 μm, $\Delta\lambda$=0.4 μm 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 μm to observe evolved red stars offers three advantages: First, effects of interstellar reddening are reduced, relative to the visible (A_K=0.11A_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 $\sigma_V = \pm 0.0509/\surd \mathit{number\ of\ nights}$ 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 $\theta_{\rm UD}$. 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 $\theta_{\rm UD}$. 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 μm as it is at visible

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TABLE 1. IOTA observations of carbon Miras and S-type stars.

Star	Date	ϕ	B_p [m]	Visibility	θ_{UD} [mas]
Carbon Miras:					
S CEP	96 Jun 06	0.22	27.32	0.3672	13.67 ± 0.76
V CRB	96 May 29	0.08	37.32	0.6708	7.26 ± 0.23
V CRB	96 May 29		37.42	0.6374	
V CRB	96 May 30		37.50	0.5562	
V CRB	96 May 30		37.39	0.5919	
V CRB	96 Jun 06		35.41	0.5847	
V CRB	96 Jun 07		35.52	0.6790	
U CYG	95 Jul 09	0.57	37.43	0.6260	7.17 ± 0.58
U CYG	95 Oct 05	0.76	36.38	0.6859	6.74 ± 0.44
U CYG	95 Oct 05		36.29	0.6754	
U CYG	96 May 29	0.28	37.10	0.6576	7.05 ± 0.26
U CYG	96 May 29		37.04	0.6218	
U CYG	96 May 31		36.08	0.5874	
U CYG	96 Jun 01		35.27	0.6565	
U CYG	96 Jun 06		34.36	0.6898	
V CYG	95 Oct 05	0.25	36.88	0.0470	14.20 ± 0.77
V CYG	96 May 31	0.81	36.07	0.1846	12.54 ± 0.64
R LEP	95 Oct 07	0.99	32.40	0.3694	11.50 ± 0.64
S-Type Miras:					
R AND	95 Jul 09	0.43	37.22	0.5307	8.26 ± 0.56
R AND	95 Oct 04	0.65	36.19	0.5644	7.96 ± 0.24
R AND	95 Oct 04		35.98	0.5756	
R AND	95 Oct 05		36.73	0.6063	
R AND	95 Oct 05		36.88	0.6003	
R AND	95 Oct 08		38.21	0.5703	
R AND	95 Oct 08		38.21	0.5537	
W AQL	96 Jun 04	0.98	31.06	0.4064	11.08 ± 0.47
W AQL	96 Jun 04		30.79	0.4729	
R CYG	95 Jul 09	0.41	37.07	0.7188	6.16 ± 0.64
R CYG	95 Oct 05	0.62	37.04	0.7495	5.63 ± 0.48
R CYG	95 Oct 05		37.02	0.7720	
R CYG	96 May 29	0.18	36.80	0.6705	6.74 ± 0.27
R CYG	96 May 29		36.83	0.6613	
R CYG	96 May 31		36.10	0.6518	
R CYG	96 Jun 01		34.70	0.7196	
R CYG	96 Jun 06		34.46	0.6637	
R LYN	95 Oct 04	0.75	34.71	0.8510	5.00 ± 0.40
R LYN	95 Oct 04		34.83	0.8879	
R LYN	95 Oct 04		34.76	0.8300	
R LYN	95 Oct 04		34.87	0.7505	
R LYN	96 Mar 13	0.17	35.91	0.7585	5.84 ± 0.70
S-Type non-Miras:					
NZ GEM	96 Mar 11		36.07	0.8413	Unresolved
NZ GEM	96 Mar 11		35.94	1.1030	
HR 8062	95 Jul 10		37.64	1.0400	Unresolved
IRC 40458	96 May 29		36.82	0.9383	Unresolved
IRC 40458	96 Jun 01		35.85	0.9668	
RS CNC	96 Mar 07		21.21	0.4825	15.73 ± 0.42
RS CNC	96 Mar 07		21.20	0.5576	
RS CNC	96 Mar 07		21.18	0.4124	
RS CNC	96 Mar 07		21.21	0.4372	
RS CNC	96 Mar 07		21.21	0.4401	
AA CYG	96 May 29		36.94	0.8143	4.99 ± 0.52
AA CYG	96 Jun 06		34.61	0.8057	
AD CYG	96 May 29		37.43	1.1180	Unresolved
OP HER	95 Jun 04		37.55	0.7869	5.13 ± 0.28
OP HER	95 Jun 04		37.59	0.8202	
OP HER	95 Jun 04		37.34	0.7955	
OP HER	95 Jun 04		37.28	0.7900	
OP HER	95 Jun 05		37.48	0.7844	
OP HER	95 Jun 05		37.54	0.7843	
OP HER	96 May 28		37.26	0.7314	6.00 ± 0.45
OP HER	96 May 28		37.20	0.7270	
ST HER	95 Jun 03		36.93	0.5073	9.14 ± 0.23
ST HER	95 Jun 03		36.86	0.4653	
ST HER	95 Jun 04		36.93	0.4378	
ST HER	95 Jun 04		36.86	0.4262	
ST HER	95 Jun 05		36.90	0.4552	
ST HER	95 Jun 05		36.84	0.4462	
ST HER	96 May 29		36.75	0.4197	9.28 ± 0.28
ST HER	96 May 30		36.96	0.4718	
ST HER	96 May 30		37.00	0.4485	
ST HER	96 Jun 01		35.64	0.4510	

wavelengths. This expectation is based upon our unpublished 2.2 μm data for α Her, a supergiant star expected to have the same order of atmospheric extension as do the Mira variables. A comparison of our data with visible α Her data (Tuthill 1994) indicates that the departures from a uniform disk visibility curve are present in the visible but not the infrared. Thus we assume that to first order, a uniform disk model will also fit the Mira data; a slight correction to the derived angular sizes to account for this assumption will be discussed in Sec. 3. In this case, a single spatial frequency point will uniquely and precisely determine the angular diameters for visibilities in the approximate range $0.25 \leqslant V \leqslant 0.75$. If there are significant differences between the brightness profiles for supergiants and for Mira variables then this assumption will be invalid; this point may only be addressed by detailed multiple spatial frequency observations of the visibility curves.

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, $T_{\rm EFF}$, is defined in terms of the star's luminosity and radius by $L = 4\pi\sigma R^2 T_{\rm EFF}^4$. Rewriting this equation in terms of angular diameter θ_R and bolometric flux $F_{\rm TOT}$ a value of $T_{\rm EFF}$ was calculated from the flux and Rosseland diameter using $T_{\rm EFF} = 2341({\rm F_{TOT}}/\theta_R^2)^{1/4}$; the units of $F_{\rm TOT}$ are 10^{-8} erg/cm^2 s, and θ_R is in mas. The error in $T_{\rm EFF}$ 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: $\theta_R = 1.045\theta_{\rm UD}$, 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 ($\Delta\theta = 19°$). 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-

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TABLE 2. Phase, spectral type, and photometry.

Star	Date	ϕ	Spectral Type	V [mag]	K [mag]	L [mag]	m_{12} [mag]	m_{25} [mag]	m_{60} [mag]
Carbon Miras:									
S CEP	96 Jun 06	0.21	C7,4e(N8e)	9.50	-0.07 ± 0.15	-1.47	-2.83	-3.24	-3.47
V CRB	96 May 29	0.05	C6,2e(N2e)	8.50	1.22 ± 0.06	0.71	-1.42	-1.70	-1.81
U CYG	95 Jul 09	0.57	C7,2e-C9,2(NPe)	9.75	1.01 ± 0.11	0.05	-1.50	-1.81	-2.13
U CYG	95 Oct 05	0.76	C7,2e-C9,2(NPe)	8.00	0.89 ± 0.08	0.05	-1.50	-1.81	-2.13
U CYG	96 May 29	0.27	C7,2e-C9,2(NPe)	9.00	0.77 ± 0.04	0.05	-1.50	-1.81	-2.13
V CYG	95 Oct 05	0.23	C5,3e-C7,4e(NPe)	11.00	0.38 ± 0.48	-1.28	-3.43	-3.85	-4.04
V CYG	96 May 31	0.79	C5,3e-C7,4e(NPe)	11.50	0.50 ± 0.21	-1.28	-3.43	-3.85	-4.04
R LEP	95 Oct 06	0.99	C7,6e(N6e)	9.50	0.43 ± 0.15	-0.60	-2.82	-3.09	-3.36
S-Type Miras:									
R AND	95 Jul 09	0.43	S3,5e-S8,8e(M7e)	13.50	0.48 ± 0.02	-1.17	-2.66	-3.49	-3.27
R AND	95 Oct 04	0.65	S3,5e-S8,8e(M7e)	15.00	1.11 ± 0.02	-1.17	-2.66	-3.49	-3.27
W AQL	96 Jun 04	0.94	S3,9e-S6,9e	7.50	0.05 ± 0.08	-0.84	-4.36	-4.99	-4.93
R CYG	95 Jul 09	0.43	S2.5,9e-S6,9e(Tc)	12.00	1.05 ± 0.04	0.20	-1.42	-2.22	-2.50
R CYG	95 Oct 05	0.64	S2.5,9e-S6,9e(Tc)	14.00	1.49 ± 0.05	0.20	-1.42	-2.22	-2.50
R CYG	96 May 29	0.20	S2.5,9e-S6,9e(Tc)	9.00	0.66 ± 0.05	0.20	-1.42	-2.22	-2.50
R LYN	95 Oct 04	0.72	S2.5,5e-S6,8e:	10.50	2.30 ± 0.23	1.06	0.49	0.19	-0.13
R LYN	96 Mar 13	0.15	S2.5,5e-S6,8e:	8.50	2.21 ± 0.90	1.06	0.49	0.19	-0.13
S-Type non-Miras:									
RS CNC	96 Mar 07		M6eIb-II(S)	5.95	-1.67 ± 0.10	-2.00	-3.07	-3.73	-3.59
AA CYG	96 May 29		S7,5-S7.5,6(MPTc)	8.40	0.65 ± 0.11		-0.37	-0.90	-1.62
OP HER	95 Jun 04		M5IIb-IIIa(S)	6.32	0.03 ± 0.02	-0.15	-0.70	-1.01	-1.12
OP HER	96 May 28		M5IIb-IIIa(S)	6.32	0.16 ± 0.21	-0.15	-0.70	-1.01	-1.12
ST HER	95 Jun 03		M5IIb-IIIa(S)	6.70	-0.78 ± 0.01	-0.83	-2.12	-2.90	-2.87
ST HER	96 May 29		M6-7IIIaS	6.70	-0.58 ± 0.10	-0.83	-2.12	-2.90	-2.87

per I for details). Contemporaneous V band measurements were obtained from the available AFOEV visual data for the variable stars (Schweitzer 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 $F_{\rm TOT}$, with A_K of marginal effect on m_K ($A_K \leq 0.06$), 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 $F_{\rm TOT}$ 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 χ^2 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 weight in the fit.

Error in the estimation of $F_{\rm TOT}$ 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 $\Delta m_V = \pm 1.0$ mag for the V band data from the AFOEV archive. The error L band data, $\Delta m_L = \pm 0.25$ 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 $F_{\rm TOT}$. Given the reddening for the carbon stars found in Claussen *et al.* (1987), an average reddening of $A_K = \pm 0.06$ was adopted as an additional source of error for the S-type stars. Errors in the estimation of $F_{\rm TOT}$ were added in quadrature to obtain a final $F_{\rm TOT}$ error value.

4. LINEAR RADII

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 Mira and non-Mira S/stars, Yorka & Wing (1977) suggest that maximum light $M_V = -1.6$ and -1, 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,

TABLE 3. Derived stellar parameters.

Star	Date	F_{TOT}	error	Model	θ_R [mas]	T_{EFF} [K]	*D1* [pc]	*D2* [pc]	*D3* [pc]	*Est'd D* [pc]	*D Hip [pc]*	*D [pc]*	*R* [$R_\odot$]
Carbon Miras:													
S CEP	96 Jun 06	140.80 ± 11.59	K	1.045	14.29 ± 2.28	2133 ± 176	560	404		482 ± 96	415 ± 105	451 ± 71	693 ± 155
V CRB	96 May 29	47.70 ± 6.52	V	1.045	7.59 ± 1.16	2233 ± 188		732		732 ± 146	1961 ± 3576	734 ± 146	599 ± 151
U CYG	95 Jul 09	57.20 ± 8.08	K=V	1.045	7.50 ± 1.28	2351 ± 217		629		629 ± 126	901 ± 625	640 ± 123	515 ± 133
U CYG	95 Oct 05	76.30 ± 14.17	V	1.045	7.04 ± 1.15	2607 ± 245		629		629 ± 126	901 ± 625	640 ± 123	484 ± 122
U CYG	96 May 29	75.60 ± 8.19	V	1.045	7.37 ± 1.14	2543 ± 208		629		629 ± 126	901 ± 625	640 ± 123	506 ± 125
V CYG	95 Oct 05	105.70 ± 13.40	K=L	1.045	14.84 ± 2.37	1949 ± 167	580	510		545 ± 109	271 ± 130	432 ± 84	689 ± 173
V CYG	96 May 31	101.20 ± 12.53	L	1.045	13.10 ± 2.08	2051 ± 174	580	510		545 ± 109	271 ± 130	432 ± 84	608 ± 152
R LEP	95 Oct 06	86.00 ± 12.73	K	1.045	12.00 ± 1.92	2058 ± 181	410	508		459 ± 92	251 ± 53	303 ± 46	391 ± 86
S-Type Miras:													
R AND	95 Jul 09	85.80 ± 5.87	L	1.045	8.63 ± 1.42	2424 ± 204	240	609	746	532 ± 106		532 ± 106	493 ± 128
R AND	95 Oct 04	68.20 ± 9.35	L	1.045	8.32 ± 1.27	2332 ± 195	240	609	746	532 ± 106		532 ± 106	476 ± 120
W AQL	96 Jun 04	129.40 ± 21.39	V=R	1.045	11.58 ± 1.80	2320 ± 205		427	832	629 ± 126		629 ± 126	783 ± 199
R CYG	95 Jul 09	47.20 ± 5.48	R	1.045	6.44 ± 1.18	2419 ± 232	420	689	661	590 ± 118		590 ± 118	408 ± 111
R CYG	95 Oct 05	33.50 ± 2.26	K=L	1.045	5.89 ± 1.02	2321 ± 204	420	689	661	590 ± 118		590 ± 118	373 ± 99
R CYG	96 May 29	71.20 ± 6.10	R	1.045	7.05 ± 1.09	2561 ± 206	420	689	661	590 ± 118		590 ± 118	447 ± 113
R LYN	95 Oct 04	17.00 ± 2.91	K	1.045	5.23 ± 0.89	2078 ± 198		1178	832	1005 ± 201		1005 ± 201	565 ± 148
R LYN	96 Mar 13	19.50 ± 10.63	K=V	1.045	6.10 ± 1.17	1991 ± 332		1178	832	1005 ± 201		1005 ± 201	659 ± 183
S-Type non-Miras:													
RS CNC	96 Mar 07	676.90 ± 9.62	K	1.022	16.07 ± 0.43	2977 ± 42	170		245	208 ± 42	122 ± 15	131 ± 14	227 ± 24
AA CYG	96 May 29	74.00 ± 9.79	V=K=R	1.022	5.10 ± 0.53	3041 ± 189		550	759	654 ± 131	1163 ± 1190	661 ± 130	362 ± 81
OP HER	95 Jun 04	147.70 ± 1.29	V	1.022	5.24 ± 0.29	3564 ± 99			291	291 ± 58	307 ± 51	300 ± 38	169 ± 24
OP HER	96 May 28	145.90 ± 2.74	V	1.022	6.13 ± 0.46	3286 ± 125			291	291 ± 58	307 ± 51	300 ± 38	198 ± 29
ST HER	95 Jun 03	279.20 ± 23.87	V	1.022	9.34 ± 0.23	3131 ± 77			347	347 ± 69	311 ± 72	330 ± 50	331 ± 51
ST HER	96 May 29	235.90 ± 29.70	K=V	1.022	9.48 ± 0.29	2979 ± 104			347	347 ± 69	311 ± 72	330 ± 50	336 ± 52

Distance references: carbon Miras: 1 Rowan-Robinson & Harris (1983b), 2 Claussen *et al.* (1987) (M_K = -8.1); S Miras 1 Rowan-Robinson & Harris (1983a), 2 Jura (1988) (M_K = -8.1), 3 Yorka & Wing (1977) (M_V = -1.6); S non-Miras 1 Rowan-Robinson & Harris (1983a), 2 Jura (1988), 3 Yorka & Wing (1977) (M_V = -1.0); *D Hip* ESA (1997).

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's 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-Mira S star 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 $\Delta T_{\rm EFF}\approx 225$ K between the oxygen-rich and S-type stars, while $\Delta T_{\rm EFF}\approx 200$ 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 $\Delta T_{\rm EFF}\approx 650$ 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-

TABLE 4. General trends of effective temperatures and radii.

	Mira	Type difference	Ref.	non-Mira	Type difference	Ref.	Mira / non-Mira difference
Effective Temperatures (K):							
oxygen-rich	2654 ± 30		2	3260 ± 17		3	606
		327			179		
S-type	2327 ± 76		1	3081 ± 31		1	754
		133			208		
carbon	2194 ± 67		1	2873 ± 26		4	679
Radii ($R_\odot$):							
oxygen-rich	367 ± 68		2	160 ± 40		3	207
		159			110		
S-type	526 ± 138		1	270 ± 82		1	256
		35			130		
carbon	561 ± 105		1	400 ± 100		4	161

References:

1 This paper, 2 van Belle *et al.* 1996, 3 Dyck *et al.* 1996a, 4 Dyck *et al.* 1996b.

Notes:

1 Oxygen-rich non-Mira temps from stars later than M4 in Dyck *et al.* 1996a.

2 Oxygen-rich non-Mira radii from M7 estimate & Dyck *et al.* 1996a.

3 Error bars on oxygen-rich and carbon non-Miras were not given in the references and hence assumed to be 25%.

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 σ_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 $\Delta R = 110-160 R_\odot$ between the oxygen-rich and S-type stars, while ΔR is roughly 35–130 $R_\odot$ between the S-type and carbon stars; the increase in size is toward those stars that are believe 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 subclasses 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 ΔR of approximately 160–260 $R_\odot$ between types, with the Miras being larger.

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