

ANGULAR DIAMETER MEASUREMENTS OF COOL GIANT STARS IN STRONG TiO BANDS
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ABSTRACT

We present angular diameter measurements of 15 giant and supergiant stars in the strong TiO absorption band at 712 nm and in a continuum band at 754 nm with the MkIII long-baseline interferometer. While relatively warm giant stars (spectral types K5 III or M0 III) have identical diameters measured with the two filters, cooler stars (spectral types M3 III to M5 III) appear $\sim 10\%$ larger at 712 nm than at 754 nm. This effect is even more pronounced in luminosity class I stars. It can be understood by noting that the tenuous and extended stellar atmospheres of cool stars become opaque in TiO absorption bands at a significantly larger radius than in the continuum; i.e., we measure directly the physical extension of the stellar atmospheres. This is a novel method for testing models of cool star atmospheres.

Subject headings: stars: atmospheres — stars: fundamental parameters — stars: giants — techniques: interferometric

1. INTRODUCTION

The first direct measurements of angular diameters of stars other than the Sun were made possible by the development of stellar interferometry around 1920 (Michelson & Pease 1921). Mainly during the last 30 years, stellar diameters have been obtained by lunar occultation measurements, speckle methods, and intensity as well as amplitude interferometry. Accurate angular diameters are needed to calibrate the effective temperatures derived from photometric data with the help of model atmospheres, and they can help to check the validity of the models used in this process. With the recent progress in interferometric methods, it has become possible to measure not only precise angular diameters, but also their variation with wavelength for individual stars; these measurements can be used to obtain additional information on the atmospheres of these stars.

Variations of measured stellar diameters with wavelength can be caused either by wavelength-dependent limb darkening, or by true variations of the photospheric radius with wavelength. The effect of limb-darkening can be predicted from model atmospheres (e.g., Hanbury Brown, Davis, & Thompson 1974), and the apparent wavelength dependence of stellar radii due to limb darkening has been measured by lunar occultations (Ridgway et al. 1982) and with the MkIII stellar interferometer (Mozurkewich et al. 1991). Since the limb-darkening correction depends on the model atmosphere used, most observers quote both model-independent uniform disk diameters (i.e., the best fit to the data with the assumption of no limb darkening) and model-dependent limb-darkened diameters. We follow this convention here. True variations of the stellar diameter with wavelength have been found in the Mira variables α Cet (Labeyrie et al. 1977; Bonneau et al. 1982) and R Leo (Di Giacomo et al. 1991): The outer atmospheres of these stars are so tenuous and extended that they become opaque at a substantially larger radius in TiO absorption

bands than in the continuum. Therefore the stellar diameter measured in a given bandpass increases strongly with the strength of TiO absorption within that bandpass.

Here we report angular diameter measurements of 15 “normal” (i.e., non-Mira) late-type giant and supergiant stars inside the strong TiO band at 712 nm and in a continuum filter at 754 nm. We show that these stars exhibit an effect similar to the one previously seen in Mira variables and that its strength depends on spectral type and luminosity class.

2. OBSERVATIONS AND DATA REDUCTION

The observations were carried out using the variable baseline of the MkIII stellar interferometer on Mount Wilson.⁴ The MkIII is a fringe-tracking Michelson interferometer, with a limiting magnitude for cool stars of $m_V \approx 5.3$; its variable north-south baseline can be configured to lengths between 3.0 and 31.5 m. Detailed descriptions of the instrument and the observing and calibration procedures have been given by Shao et al. (1988) and Mozurkewich et al. (1991). For the observations reported here, only baseline lengths between 3.0 and 11.4 m were used.

To investigate the dependence of the diameters of late-type stars on the TiO absorption strength, we used three filters matched to strong TiO bands at 623, 672, and 712 nm, and two comparison filters in relatively uncontaminated continuum bands at 701 and 754 nm; see Table 1. (For representative spectra of cool stars see Turnshek et al. 1985.) Most of the observations were carried out using the 712 and 754 nm filters, which are similar to the filters used in the Wing photometric system to measure the TiO absorption index (White & Wing 1978).

To select the program stars, we compiled a list of all stars with spectral types K, M, C, or S that have magnitudes $m_V \leq 5.3$, expected angular diameters $D \geq 3.5$ mas, and declinations $\delta \geq -28^\circ$. For each program star, a nearby star with small diameter was chosen as a visibility calibrator. The observing

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⁴ The MkIII Optical Interferometer located on Mount Wilson near Los Angeles, CA, is jointly operated by the Center for Advanced Space Sensing of the Naval Research Laboratory (NRL) and by the US Naval Observatory (USNO).

TABLE 1
CENTRAL WAVELENGTHS λ_c AND WIDTHS (FWHM) OF THE FILTERS USED^a

Filter Numbers	λ_c (nm)	$\Delta\lambda$ (nm)	Function	UDD of β Peg (mas)
1.....	623	9	TiO	18.13 ± 0.26
2.....	672	6	TiO	17.79 ± 0.24
3.....	701	6	Continuum	16.83 ± 0.19
4.....	712	12	TiO	17.55 ± 0.14
5.....	754	5	Continuum	16.11 ± 0.11

^a The last column gives the uniform disk diameter of the star β Pegasi as measured in the individual filters.

lists for individual nights consisted of about 10 program stars along with their calibrators. We performed scans of 75–300 s duration on each star and kept cycling through the observing list throughout the night.

The primary output of the interferometer is the square of the raw visibility amplitude for each interval of 4 ms. These visibility data were averaged for each scan and corrected for dark counts, which were measured separately on blank sky. The calibrator stars were used to determine the system visibility as a function of seeing, zenith angle, time, and angle of incidence on the siderostat mirrors; the residual scatter of the visibilities of the calibrator stars around this fit was used to estimate the calibration uncertainty. Raw visibility data of the program stars were then divided by the system visibility to give the calibrated squared visibilities. The calibration uncertainty and the photon noise were added quadratically to give the error estimate for the calibrated squared visibilities.

To determine the stellar diameters, we fitted uniform disk models to the combined visibility data of each star, separately for the different wavelengths. The best-fit model was found by minimizing the χ^2 of the data points. An error estimate for the

diameter (68% confidence) was determined from the increase of χ^2 when the diameter was varied. Finally, we calculated the ratio of the stellar diameters at 712 and at 754 nm; the error for this ratio was obtained by adding the relative errors for the two diameters quadratically. This procedure should give conservative error estimates, since it assumes that the errors of the diameters at the two wavelengths are independent from each other, while they probably are positively correlated because data at 712 and at 754 nm were always taken simultaneously.

3. RESULTS

Figure 1 shows the visibility data for the star β Peg; each data point corresponds to one 75 s scan. Open circles are measurements at 712 nm; filled circles are at 754 nm. The two heavy lines are the theoretical curves for uniform disks with diameters of 16.1 and 17.6 mas, respectively; these are the best-fit values for the two data sets. From this figure it is apparent that uniform disk models give a good representation of the data over a wide range of baselines, and that there is a very significant ($\sim 12\sigma$) difference in the diameters at the two wavelengths.

In Table 2 we list those stars for which we have determined diameters with accuracies of $\sim 3\%$ or better. For the stars α Tau and β Peg, the formal errors are smaller than 1%. Consequently, the (conservative, see above) error estimates for the 712/754 nm diameter ratios range from ~ 1 to $\sim 4\%$. Figure 2 shows the diameter ratio as a function of $R-I$ color index. Stars of luminosity classes II or III are represented by open circles; filled circles represent luminosity class I stars. This figure indicates that the diameter ratio increases with $R-I$, and that for a given color index it is larger for luminosity class I than for class II or III stars.

We have also collected some data on the stars α Ori, α Her, and σ Cet. These stars are so large that they are heavily resolv-

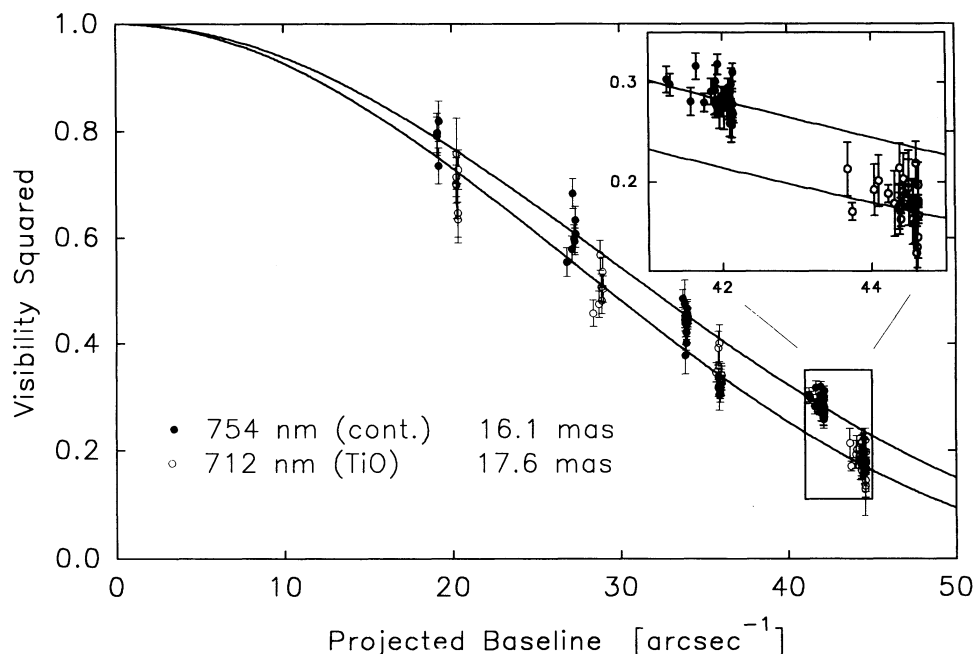


FIG. 1.—Visibility measurements of β Peg. The data points represent individual scans of 75 s.

TABLE 2
SUMMARY OF RESULTS^a

Star	BS	Spectral Type	$R-I$	UDD at 712 nm (mas)	UDD at 754 nm (mas)	Diameter Ratio
β And	337	M0 IIIa	1.00	12.73 ± 0.18	12.63 ± 0.22	1.01 ± 0.02
α Cet	911	M1.5 IIIa	1.00	11.95 ± 0.23	11.66 ± 0.22	1.02 ± 0.03
ρ Per	921	M4 II	1.62	16.03 ± 0.29	14.66 ± 0.20	1.09 ± 0.02
α Tau	1457	K5 III	0.94	19.88 ± 0.14	19.80 ± 0.12	1.00 ± 0.01
119 Tau	1845	M2 Iab-Ib	1.44	11.47 ± 0.33	9.98 ± 0.20	1.15 ± 0.04
π Aur	2091	M3 II	1.31	8.90 ± 0.29	8.23 ± 0.21	1.08 ± 0.04
η Gem	2216	M3 III	1.31	11.75 ± 0.27	10.70 ± 0.15	1.10 ± 0.03
μ Gem	2286	M3 IIIab	1.38	13.97 ± 0.28	13.50 ± 0.13	1.03 ± 0.02
δ Lyr	7139	M4 II	1.63	11.76 ± 0.30	10.85 ± 0.26	1.08 ± 0.04
R Lyr	7157	M5 III	1.91	18.66 ± 0.31	16.64 ± 0.25	1.12 ± 0.02
μ Cep	8316	M2 Iae	1.76	25.03 ± 0.43	21.31 ± 0.28	1.17 ± 0.02
β Peg	8775	M2.5 II-III	1.32	17.55 ± 0.14	16.11 ± 0.11	1.09 ± 0.01

^a For each star, the table lists the Bright Star number, spectral type, $R-I$ color index, uniform disk diameters at 712 and 754 nm, and the ratio of these diameters.

ed even on the shortest baselines of the MkIII Interferometer. Since it is known that both α Ori and α Cet have pronounced surface structure (Buscher et al. 1990; Quirrenbach et al. 1992), and since α Her is a multiple system, uniform disk diameters based on a very limited baseline range might be misleading. Therefore, these stars are not included in Table 2. However, the visibility data on these stars show clearly that they also have considerably larger diameters at 712 nm than at 754 nm. In fact, the data on α Ori, and α Her, support the conclusion that luminosity class I stars have a particularly large 712/754 nm diameter ratio, and α Cet shows by far the largest diameter ratio of all stars that we have observed, confirming the results by Labeyrie et al. (1977) and Bonneau et al. (1982).

For most of our program stars we have not yet been able to obtain enough data at 623, 672, or 701 nm to determine reliable diameters. For the best-observed star in our sample, β Peg, however, we give the uniform disk diameters in all five filters in Table 1. The two smallest diameters are those measured in the two "continuum" filters. The larger diameter at 701 nm as compared to 754 nm might be due to stronger contamination of TiO in this filter; likewise, the differences of the diameters in the TiO bands at 623, 672, and 712 nm might be due to differences in the TiO absorption strengths.

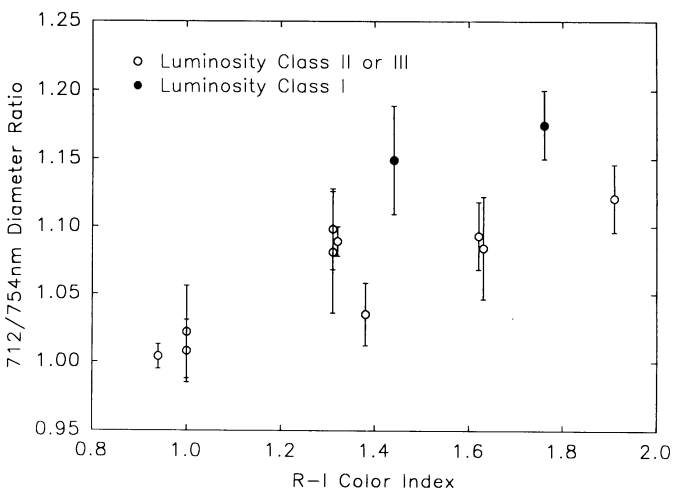


FIG. 2.—Ratio of the uniform disk diameters measured at 712 and 754 nm as a function of $R-I$ color index.

4. DISCUSSION

Since all diameters given above are uniform disk diameters, we have to address the question whether differences in limb darkening might account for the observed differences in the angular diameters. For two reasons, this cannot be the case: First, the observed diameter differences are too large to be explained solely by limb darkening effects; in μ Cep the limb darkening corrections at 712 nm and 754 nm would have to differ by 17%. However, even the extreme case of a fully limb darkened disk gives a correction of only 13%, and values of $\sim 7\%$ are more typically expected from model atmosphere calculation for cool stars at the wavelengths of interest (Manduca 1979). Second, limb darkening is expected to be substantially larger in the visible than in the IR. Therefore measured uniform disk diameters must be smaller in the visible than in the IR, if the physical photospheric radius is constant with wavelength. A comparison with diameters at 2.2 μ m from the CERGA I2T interferometer (see below) shows that the opposite is the case for the 712 nm data: uniform disk diameters at this wavelength are clearly larger than at 2.2 μ m. Therefore we conclude that we have observed real variations of the physical diameters of cool stars with wavelength; i.e., we have directly measured the extension of the stellar atmospheres.

This wavelength dependence of the angular diameter of cool giant stars due to variations of the TiO absorption strength is a new and potentially powerful source of information about the structure of stellar atmospheres. The same dependence has been investigated for the Mira variables α Cet (Labeyrie et al. 1977; Bonneau et al. 1982) and R Leo (Di Giacomo et al. 1991), but quantitative comparison with predictions from model atmosphere calculations (e.g., Scholz & Takeda 1987; Bessell et al. 1989) are difficult because of the time variability, highly complex atmospheric structure, and uncertainties in the effective temperatures. Therefore, "normal" giant and supergiant stars seem better suited for a confrontation with theoretical models, although the variations of the stellar diameters with TiO strength are much smaller in these stars. The data presented in this paper show indeed that modern long-baseline interferometry can provide angular diameters with sufficient accuracy to allow meaningful investigations of their wavelength dependence.

Qualitatively, the increase of the 712/754 nm diameter ratio with the $R-I$ color index is expected and easy to understand: For comparatively warm stars like α Tau (spectral type K5 III)

the TiO strength is fairly small, and the atmosphere is only moderately extended, so that the stellar diameters measured in the continuum and inside the TiO band are coincident to within $\sim 1\%$. For the cooler stars (spectral types M3 through M5), both the TiO strength and the atmospheric extension are much larger, and the measured uniform disk diameters at 712 and 754 nm differ by as much as $\sim 10\%$. The supergiants 119 Tau and μ Cep have spectral types of M2, indicating that they have only moderate TiO absorption. (The MK classification of M stars is mostly based on TiO absorption strength.) Nevertheless, they show an even larger 712/754 nm diameter ratio, probably due to the more extreme extension of their atmospheres. It is also possible that TiO in the supergiant winds contributes to the large diameters measured at 712 nm.

A more quantitative understanding of the wavelength dependence of stellar diameters requires a careful comparison with model atmosphere computations, including both the effects of atmospheric extension and limb darkening. To first order, a limb-darkened star appears to an interferometer like a somewhat smaller star with uniform brightness. Only data taken close to and beyond the first null of the visibility function can determine limb darkening observationally; unfortunately these data are difficult to obtain and have always much poorer signal-to-noise ratios than data in the high-visibility regime. Therefore limb darkening information from model atmospheres is normally used to convert the (purely observational) uniform disk diameters to physical photospheric diameters (e.g., Hanbury-Brown et al. 1974). For cool stars, exact limb darkening corrections cannot easily be computed from published limb darkening tables, since the spatial brightness distribution of the star has to be properly integrated over the filter bandpasses to account for changes of the TiO absorption strength within the filters. This problem has been discussed for the extreme case of Mira variables by Scholz & Takeda (1987), who show that the apparent limb darkening can depend quite dramatically not only on the central wavelengths, but also on the widths of the filters used. (Our 754 nm filter is similar to their filter 3n, whereas our 712 nm filter is intermediate between their filters 2n and 2w.) When these effects are taken into account, it should be possible to compare the observational 712/754 nm diameter ratios to those predicted by model atmospheres and thereby test the validity and underlying assumptions of these models. In addition, precise effective temperatures could be derived from the limb-darkened diameters and photometric information.

Several stars in our observing list are strongly variable, notably R Lyr, and μ Cep. Although the photometric variations of these stars are so large that the diameters might vary noticeably, we have not obtained sufficient data to look for

temporal changes. It should be noted, however, that the data at 712 and 754 nm were always taken simultaneously to minimize the effect of variability on the diameter ratios.

For a quantitative comparison of the observational results with model atmospheres, it is desirable to obtain data in a continuum filter with as little TiO contamination as possible. Although the filter at 754 nm probably represents the best continuum band within the range accessible to the MkIII interferometer ($450 \text{ nm} \lesssim \lambda \lesssim 850 \text{ nm}$), it still has some contamination, especially for very cool stars. A comparison with infrared diameters could help assess the influence of this contamination on our "continuum" diameters. Six of the stars in Table 2 have been observed with the CERGA I2T interferometer at $2.2 \mu\text{m}$ (Di Benedetto & Rabbia 1987). In Table 3 we list the infrared diameters together with our measurements. For a comparison of the results, estimates of the limb darkening at the different wavelengths are needed, as discussed above. Taking the model for $T_{\text{eff}} = 3750 \text{ K}$, $\log g = 1.5$ from Manduca (1979) as a rough guideline, we expect limb darkening corrections of $\sim 3.0\%$ at $2.2 \mu\text{m}$, $\sim 6.1\%$ at 800 nm, and $\sim 7.8\%$ at 700 nm. Using corrections of 3% at $2.2 \mu\text{m}$ and 7% at 754 nm, we find that the $2.2 \mu\text{m}$ diameter for β And is larger than the 754 nm diameter, the results for ρ Per agree well, and for the other four stars a smaller diameter is found in the infrared than at 754 nm. Based on anomalously high visibility measurements around the expected first null of the visibility function, Di Benedetto & Bonneau (1990) conclude that β And shows small-scale structure (star spots or a small companion) at $2.2 \mu\text{m}$. Consequently there are more free parameters to model the surface brightness distribution of this star, and it is quite possible that the infrared diameter is substantially smaller than the quoted value. Excluding this star from the comparison, four out of five stars appear to have smaller diameters at $2.2 \mu\text{m}$ than at 754 nm, with differences of a few percent. It seems unlikely, however, that these differences are due to true wavelength dependencies of the monochromatic diameters or to TiO contamination in the 754 nm filter, since they do not show a trend with spectral type. Especially for the fairly warm star α Tau, no difference between the 754 nm and $2.2 \mu\text{m}$ diameters would be expected.

Another explanation would involve a systematic bias in one of the two data sets. Since the diameters from the MkIII interferometer are based on a large number of well-calibrated data obtained on a wide range of different baselines (see Fig. 1), any peculiarities would normally be detected in the data reduction process. If, for example, there were substantial flux in a star-spot or small companion, a deviation of the visibility curve from the Bessel function model would be noticed. The absolute scale of the instrument is given by the baseline length and by

TABLE 3
COMPARISON WITH INFRARED DIAMETERS^a

Star	UDD at 754 nm (mas)	UDD at $2.2 \mu\text{m}$ (mas)	LDD at 754 nm (mas)	LDD at $2.2 \mu\text{m}$ (mas)
β And	12.63 ± 0.22	13.85 ± 0.18	13.51	14.27
ρ Per	14.66 ± 0.20	15.02 ± 0.16	15.69	15.47
α Tau	19.80 ± 0.12	19.60 ± 0.29	21.19	20.19
μ Gem	13.50 ± 0.13	13.50 ± 0.15	14.45	13.91
R Lyr	16.64 ± 0.25	15.39 ± 0.36	17.80	15.85
β Peg	16.11 ± 0.11	16.19 ± 0.23	17.24	16.68

^a From Di Benedetto & Rabbia (1987). Limb darkened diameters have to be regarded with caution (see text).

the effective filter wavelengths; both quantities are known at least to one part in 10^4 . Therefore we find it very hard to believe that a systematic bias of a few per cent should be present in the MkIII data. More cross-checks between MkIII and CERGA diameters and more reliable limb darkening calculations are probably needed before the data from the two instruments can be combined in an analysis of the dependence of stellar diameters on TiO absorption strength.

The wavelength dependence of the diameters of cool stars contains a wealth of astrophysical information, which can be explored in more detail by current and future long-baseline interferometers. With the MkIII interferometer, it should be possible to obtain data similar to those presented here for about 40 stars in four or five filters. (Data in the 623 nm filter are often affected by scattered light from the HeNe laser in the delay line metrology system.) This would increase the statistical basis necessary for a comparison with model atmosphere calculations. Long-baseline interferometers of the next generation, which are currently under construction at several

institutions, should dramatically increase the efficiency and scope of similar observations. For example, with the Big Optical Array, which is being built by the Naval Research Laboratory and the US Naval Observatory at the site of Lowell Observatory, it will be possible to observe stars down to $m_V \sim 9$ in 16 wavelength channels and on 10 baselines simultaneously. Spectrally resolved interferometry in the infrared will certainly create additional possibilities. The ESO-VLT interferometer will have enough sensitivity to determine the spatial structure of Mira variables in the numerous infrared lines and thereby give new insights in the formation and propagation of the shocks which play such an important role in the tenuous atmospheres of these stars.

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REFERENCES

- Bessel, M. S., Brett, J. M., Scholz, M., & Wood, P. R. 1989, *A&A*, 213, 209
 Bonneau, D., Foy, R., Blazit, A., & Labeyrie, A. 1982, *A&A*, 106, 235
 Buscher, D. F., Haniff, C. A., Baldwin, J. E., & Warner, P. J. 1990, *MNRAS*, 245, 7
 Di Benedetto, G. P., & Bonneau, D. 1990, *ApJ*, 358, 617
 Di Benedetto, G. P., & Rabbia, Y. 1987, *A&A*, 188, 114
 Di Giacomo, A., Richichi, A., Lisi, F., & Calamai, G. 1991, *A&A*, 249, 397
 Hanbury Brown, R., Davis, J., & Thompson, R. J. 1974, *MNRAS*, 167, 475
 Labeyrie, A., Koechlin, L., Bonneau, D., Blazit, A., & Foy, R. 1977, *ApJ*, 218, L75
 Manduca, A. 1979, *A&AS*, 36, 411
 Michelson, A. A., & Pease, F. G. 1921, *ApJ*, 53, 249
 Mozurkewich, D., Johnston, K. J., Simon, R. S., Bowers, P. F., Gaume, R. A., Hutter, D. J., Colavita, M. M., & Shao, M. 1991, *AJ*, 101, 2207
 Quirrenbach, A., Mozurkewich, D., Armstrong, J. T., Johnston, K. J., Colavita, M. M., & Shao, M. 1992, *A&A*, 259, L19
 Ridgway, S. T., Jacoby, G. H., Joyce, R. R., Siegel, M. J., & Wells, D. C. 1982, *AJ*, 87, 1044
 Scholz, M., & Takeda, Y. 1987, *A&A*, 186, 200
 Shao, M., et al. 1988, *A&A*, 193, 357
 Turnshek, D. E., Turnshek, D. A., Craine, E. R., & Boeshaar, P. C. 1985, *An Atlas of Digital Spectra of Cool Stars* (Tucson: Western Research Company)
 White, N. M., & Wing, R. F. 1978, *AJ*, 222, 209