NARROW-BAND PHOTOMETRY OF RED VARIABLES IN GLOBULAR CLUSTERS

ROBERT F. WING*

Perkins Observatory, The Ohio State and Ohio Wesleyan Universities, Ohio, U.S.A.

Abstract. Fourteen red variables in the southern globular clusters 47 Tuc, ω Cen, and NGC 362 have been observed on an eight-color system of narrow-band photometry in the near infrared. Temperatures are derived from blackbody fits to the calibrated fluxes, and spectral types are given for the M stars. The types observed for the three Mira variables in 47 Tuc range from M3.1 to M7.5; two small-range variables in the same cluster are later than M4. The variables in ω Cen are mostly earlier than K5, but spectra of types M3 and M0 were also encountered among radial-velocity members. In both the metal-rich 47 Tuc and the metal-poor ω Cen, the relation between TiO band strength and temperature is approximately normal. Several of these stars fall well above or below the red giant branches of their clusters in diagrams of infrared magnitude against temperature. Comparisons are made with recent results obtained at Radcliffe Observatory on some of the same stars.

1. Introduction

Red variable stars have long been known to occur in several globular clusters. Approximately one-fourth of the globular clusters listed in the recent catalogue by Sawyer Hogg (1973) contain variables which are cooler than Cepheids, or at least seem likely to be from the data given. Most of these are semi-regular variables with periods between 50^d and 150^d; others are irregular variables, or Miras with periods near 200^d.

Although many of these stars are among the brightest members of their clusters, rather little is known about their spectra. Despite the efforts of Joy (1949), Feast and Thackeray (1960), and others who have furnished spectral classifications based upon slit spectrograms, as well as the recent work at the Radcliffe Observatory described at this Colloquium by Feast (1973), it can still be said that the spectra of the majority of known red variables in globular clusters have never been observed. Indeed, the discovery of many new red variables in ten clusters reported here a few minutes ago by Lloyd Evans and Menzies (1973) shows how incomplete has been our knowledge of even the occurrence of such stars.

Narrow-band photometry often compares favorably with slit spectroscopy as a technique for classifying spectra. Normally there is a gain in speed and internal accuracy, but a loss of spectroscopic detail and an increased likelihood of misinterpretation. For most spectral types the features used spectroscopically as classification criteria are too weak to be measured conveniently by photometry; the photometrist must then measure some stronger feature which correlates with spectral type, and rely upon this correlation in assigning a type. In the case of the M stars, on the other hand, the primary spectroscopic criteria are the TiO bands, which can themselves be

* Visiting astronomer, Cerro Tololo Inter-American Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

J. D. Fernie (ed.), Variable Stars in Globular Clusters and in Related Systems, 164–177.

measured easily and accurately with narrow-band filters. Experience has shown that a two-color TiO index measured photoelectrically with a telescope of moderate size (40–60 in.) can give a classification for an early M star of visual magnitude 12, to the accuracy achieved spectroscopically on bright stars (about one-quarter of a sub-type), in less than 10 min. In practice, I prefer to spend more time in order to measure at additional wavelengths, so as to establish the level of the continuum as well as possible in each star and to test the presence of other molecules in addition to TiO. On the eight-color system used here, the additional measurements yield color temperatures, infrared magnitudes, and band strengths of CN and VO.

The present study was undertaken to provide spectral types and color temperatures for a sample of cool cluster variables and also to test the effectiveness of the eight-color system on fainter stars than had previously been studied in this manner. Fourteen variables in 3 southern clusters (5 in 47 Tucanae, 8 in ω Centauri, and 1 in NGC 362) were observed either once or twice each in the course of three trips to Cerro Tololo Inter-American Observatory (CTIO) in 1970 and 1971. Similar observations in the northern hemisphere are planned but so far have been prevented by poor weather.

The more extensive observing program begun at Radcliffe Observatory in 1971 and discussed by Feast (1973) has been entirely independent of my work but has had essentially the same objectives. By augmenting image-tube spectrograms with infrared wide-band photometry, the Radcliffe observers have been able to obtain spectral types, temperature indices, and infrared magnitudes, i.e. the same information as provided by the eight-color photometry. It is not surprising that they too have given initial emphasis to the variables in the bright, rich clusters 47 Tuc and ω Cen. A comparison of our results is given in the last section of this paper.

2. Observations

The eight-color photometric system, designed in 1969 on the basis of earlier scanner measurements made at Lick Observatory, uses interference filters averaging 55 Å in width and ranging in wavelength from 7100 Å to 11000 Å. Three molecules are specifically measured by the program: TiO by filter 1 (the filters are numbered in order of increasing wavelength), CN by filters 4 and 8, and VO by filter 6. In late M stars the continuum is defined by the measurements in filters 2 and 5, while filters 3 and 7 serve this purpose in carbon stars. In K and early M stars, several of the filters measure nearly clean continuum regions. The measurements are reduced to a system of absolute fluxes so that comparisons with blackbodies or model atmospheres can be made. More detailed information on the photometric system is given in Wing (1971), where representative eight-color 'spectra' are also shown.

The selection of stars to observe was based largely upon the atlas of Fourcade *et al.* (1966), on which are marked all known variables in globular clusters south of declination $-29°$. Since most of the red variables in this atlas are found in the two giant clusters 47 Tuc and ω Cen, these clusters were given highest priority and, with one exception, the variables in other clusters have not yet been observed on this program.

A comparison of the red variables in these two clusters is of interest because 47 Tuc is much richer in metal content than ω Cen.

At maximum light the red variables in 47 Tuc and ω Cen are near $V=11$ or 12; at minimum they are typically about $V=12$ or 13, although the Mira variables in 47 Tuc reach magnitudes close to $V=15$. The $I(104)$ magnitudes of these stars, measured with filter 5 at 10400 Å, lie in the interval 7.7 to 9.7 on a scale on which Vega is zero. Approximately 20 min with the CTIO 60-in. telescope, including setting time and sky measurement, were spent on each eight-color observation. The accuracy of the fluxes can most realistically be estimated from the repeated observations that were made of several non-variable red giants in ω Cen, which will be reported elsewhere (Wing, 1973). The probable errors were found to be typically ± 0.05 mag., with photon statistics and uncertainties in the sky background contributing about equally. Contributions from other stars included within the diaphragm were usually negligible but in a few cases reached about 10%.

A. 47 TUCANAE (NGC 104)

This is a metal-rich cluster with few RR Lyrae stars and a strong condensation toward the center. Color-magnitude diagrams have been published by Wildey (1961) and Tifft (1963), while Eggen (1961, 1972) and Arp *et al.* (1963) have monitored several of the red variables. It has been known from the work of Feast and Thackeray (1960) that the giant branch defined by the non-variables extends to types as late as M2, and that several of the variables are also of type M2 or M3. The presence of three Mira variables long seemed a unique characteristic of 47 Tuc, but several Miras belonging to other metal-rich clusters have recently been found (see Feast, 1973).

Eight-color photometry has been obtained for 5 variables in 47 Tuc, namely the three Miras (V1, V2, and V3), the 165^d semi-regular variable V4, and the irregular variable V11. All five were observed in succession on 1970 June 30, within a time interval of 80 min; two of them, V1 and V4, were also observed on 1970 January 2. Prior knowledge of the spectra of these stars was rather meagre since Feast and Thackeray (1960) observed the three Miras only near maximum light and did not observe V4 or V11.

The eight-color spectra obtained on 1970 June 30 for the three Mira variables are plotted in Figure 1. As it happens, V1 was near maximum light, V2 was at an intermediate phase, and V3 was near minimum on this date. Their visual magnitudes, estimated crudely at the telescope, were 12.0, 12.5, and 14.5, respectively. By contrast, we see in the figure that their $I(104)$ magnitudes range over only about 0.7 mag., so that infrared observations are hardly more difficult at minimum than at maximum. This behavior is consistent with that of Miras in the field, for 25 of which Lockwood and Wing (1971) derived a mean amplitude of 1.0 mag. in $I(104)$. It is likely that these Miras are never as faint as $I(104)=9.0$, and they are probably the only members of any globular cluster capable of reaching magnitudes brighter than $I(104)=8.0$.

The procedure normally used to analyze spectra on the eight-color system begins with finding the blackbody curve that passes through one of the points in each group

https://doi.org/10.1017/S0252921100033480 Published online by Cambridge University Press

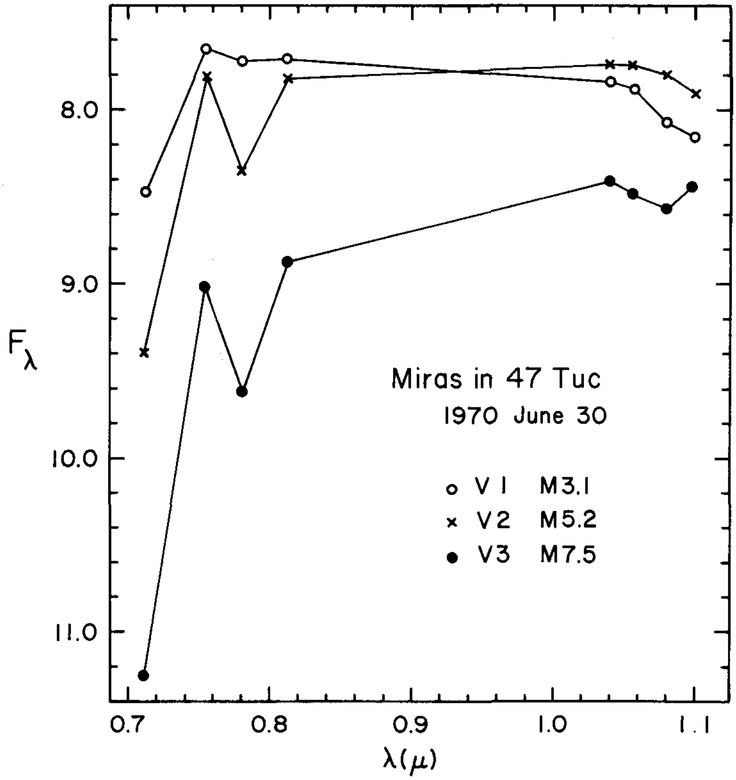

Fig. 1. Eight-color spectra of the three Mira variables in 47 Tuc obtained on 1970 June 30 at the CTIO 60-in. telescope. The fluxes are expressed on a magnitude scale. The TiO molecule is responsible for the depressions at filters 1 and 3.

of four filters and above the other points, giving directly the reciprocal color temperature $\theta = 5040/T$. Magnitude differences between the observed flux and the blackbody continuum flux at the same wavelength are then used as absorption indices, and are independent of reddening. The depression by TiO at filter 1 has been calibrated in terms of spectral type by Wing and Keenan (1973) for giant stars in the range K4 to M6. Types obtained in this manner have internal accuracies of ± 0.1 sub-type for bright stars, but in the present case of single observations of faint M stars the probable errors are about ± 0.2 sub-type.

In Figure 1, note that the spectra of V1 and V2 cross each other and that the depression of filter 1 in V3 exceeds 2 mag. V1 was clearly the warmest of the three Miras on this date and had the weakest TiO bands, while V3 was the coolest and latest. The types for V1 and V2, from the calibration of Wing and Keenan, are M3.1$\pm$0.2 and M5.2$\pm$0.2, respectively. The calibration of the TiO index does not extend beyond M6, since at later types the VO molecule appears and not only depresses the continuum at filter 2, thereby affecting the TiO index, but also supplies a more sensitive classification criterion at filter 6. Since V3 was decidedly later than M6 at the time of observation, it was classified on a preliminary scale for very late types that uses both TiO and VO. The resulting type, M7.5, has a maximum uncertainty of ± 0.5 sub-type; the great strength of TiO and the weakness of VO show that the type cannot be earlier than M7.0 or later than M8.0, respectively. The depression at filter 6 amounts to only about 2 standard deviations; if it is real and due to VO, as is normal for stars of this TiO strength, it represents the first detection of the VO molecule in a globular cluster star.

Both observations of the semi-regular variable V4 were classified M4.0, but this type must be regarded as a lower limit because a second star, only about 1.5 mag. fainter visually, had to be included in the diaphragm and no doubt 'filled in' the TiO band to some extent. Indeed, the color of V4 indicates a later type (see below). The irregular variable V11 was classified M4.4. To my knowledge, no other classifications are available for these stars.

TABLE I

Red variables in 47 Tucanae

Star	Period	Date	$I(104)$	θ	θ_0	T_0	Spectral type
V1	212^d	'70 Jan. 2	7.72	1.63	1.58	3190K	M4.0
		70 June 30	7.8	1.37	1.32	3820	M3.1
V2	203	70 June 30	7.7	1.58	1.53	3290	M5.2
V3	192	70 June 30	8.4	2.04	1.99	2530	M7.5
V4	165	70 Jan. 2	8.18	1.77	1.72	2930	> M4.0[a]
		70 June 30	8.5	1.90	1.85	2720	> M4.0[a]
V11	irr.	70 June 30	8.5	1.61	1.56	3230	M4.4

[a] The spectral type of V4 is affected by a nearby star. The color indicates a type near M5.5

The results for stars in 47 Tuc are summarized in Table I. The star names and the periods are as given in Sawyer Hogg (1973). The next two columns give the dates of observation and the $I(104)$ magnitudes; the magnitudes obtained on 1970 June 30 are uncertain by ± 0.1 mag. and are given to only one decimal place because of flexure within the cold box on that night. Next is given the reciprocal temperature θ obtained by fitting blackbody curves to the observed fluxes. These fluxes are affected by interstellar absorption which, however, is quite small in this case. Following Wing *et al.* (1973) the value $E(B-V)=0.06$ will be adopted for 47 Tuc. For a normal reddening law, the effect of this amount of interstellar material is to make the observed θ's too large by 0.05, while the corresponding absorptions in V and $I(104)$ are $A(V)=0.18$ and $A(104)=0.06$ mag., respectively. The corrected inverse temperatures θ_0 and the corresponding corrected temperatures T_0 are listed in columns 6 and 7 of Table I, and the last column gives the spectral type.

It may be noted that the temperatures and spectral types given in Table I are only rather loosely correlated with one another. To examine this effect, the TiO indices in units of 0.01 mag. have been plotted against the derived values of θ_0 in Figure 2, and

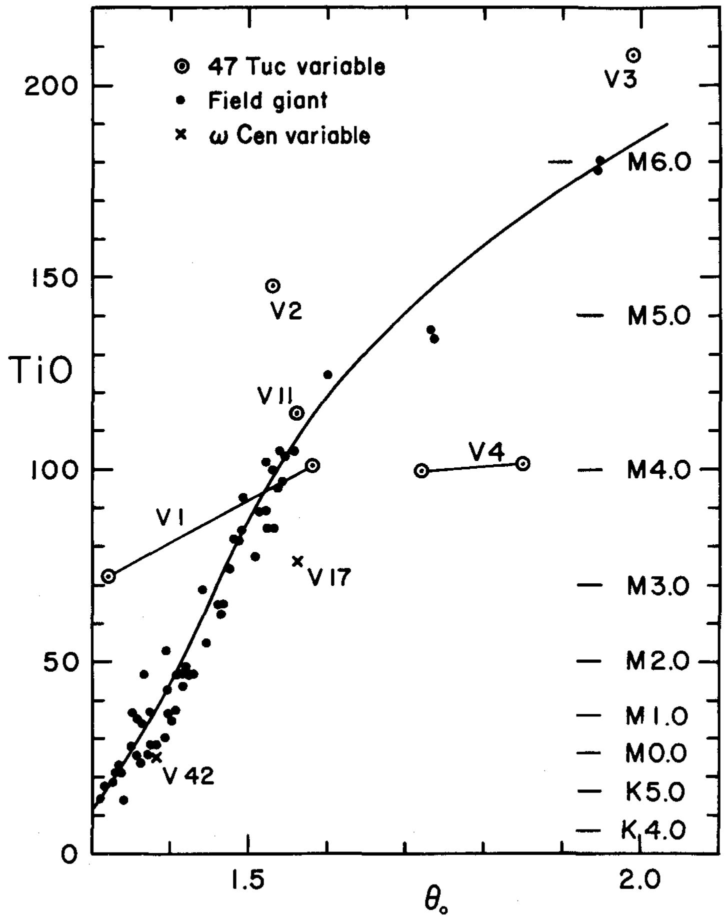

Fig. 2. The TiO index, defined as the depression at filter 1 in units of 0.01 mag., is plotted against the reciprocal color temperature θ, corrected for reddening as described in the text. The curve has been drawn through observations of bright, nearby giant stars. Different symbols are used to distinguish members of 47 Tuc and ω Cen. The calibration of the TiO index into spectral type is shown at the right.

the spectral-type calibration is shown near the right edge of the figure. For comparison with the 47 Tuc stars, a number of bright M-type giants (non-variables and small-range variables, assumed to be unreddened) observed with a CTIO 16-in. telescope in December 1969 are plotted as filled circles, and a smooth curve has been drawn through these points. For these bright stars the probable errors amount to one dot diameter in TiO and about two dot diameters in θ; for the variables in 47 Tuc the probable errors are between 2 and 3 times larger but are still much smaller than the scatter that is evident in the diagram.

Three of the four observations of Miras lie to the left of the mean giant relation in Figure 2, indicating that their colors are too blue for their types, or equivalently that their TiO bands are abnormally strong for their temperatures. Although one might be tempted to interpret this result in terms of a high oxygen-to-carbon ratio in the 47 Tuc stars, it is probably more to the point to recall that normal field Miras show the same effect. Some years ago I found that Miras trace out large loops in diagrams of band strength against color such as Figure 2, and that they are usually bluer than non-Miras of the same band strength (Wing, 1967b). The temperature found here for V1 at spectral type M3, 3820K, corresponds to that of a normal giant of type K5. Such discrepancies occur commonly among field Miras, particularly among those of relatively short period and early spectral type, and the well-documented case of R Tri has been described by Spinrad and Wing (1969). Lockwood (1972) has explored the effect further, and his Figure 7 shows that at least three-quarters of his observations of Miras with periods less than 300^d lie on the blue side of the mean giant relation between band strength and color. There is thus no evidence that the Miras in 47 Tuc differ either in O/C or in behavior from the Miras of the field.

Small-range variables normally fall quite close to the mean giant relation between band strength and color. This is the case with the single observation of V11, but both observations of V4 show it to be abnormally red for its measured TiO band strength. As we noted above, the photometry of V4 is affected by a nearby star, the effect of which should be greatest at filter 1 where M stars are faintest. Using the mean value of θ_0 obtained for V4 and the mean relation of Figure 2, we estimate the spectral type to be M5.5. This result should be confirmed with a slit spectrogram that avoids the companion.

The (0, 0) band of CN measured by filter 8 can be seen in normal giants with types as late as M3 or M4, and it is often enhanced in Mira variables. Unfortunately the noise in observations of faint stars is greater at filter 8 than elsewhere because of lower detector sensitivity, and no definite statement can be made as to the CN strengths of the red variables in 47 Tuc. If the data are taken at face value, however, they indicate a somewhat weaker CN strength than in typical field gaints of the same types, in accord with the finding of Feast and Thackeray (1960) for the K giants of the cluster. The integrated light of 47 Tuc has likewise been found by Wing *et al.* (1973) to have weaker CN absorption than is found in normal solar-neighborhood giants.

V11 is identical to star 12 in Wildey's (1961) paper. Wildey suggested that it may be a field star because it falls away from the main giant branch, being both redder in $B-V$ and somewhat fainter visually than the stars at the tip. Its measured color, $B-V=1.91$, is hard to account for, whether or not it is a member, in view of the small reddening in this direction, and it should be checked photoelectrically. However, its depressed V magnitude can readily be understood in terms of the TiO absorption that occurs at this spectral type, so that the photometry seems rather to support its membership in the cluster.

It will be useful to determine the mean absolute $I(104)$ magnitude of the Mira variables in 47 Tuc for eventual comparison with Miras in other clusters and in the field. At present the best we can do is adopt $I(104)=8.0$ for the mean apparent magnitude of these stars; with the true distance modulus $(m-M)_0=13.49$ given by Arp (1965) and the absorption $A(104)=0.06$ quoted above, we then obtain $M(104)=-5.6$

https://doi.org/10.1017/S0252921100033480 Published online by Cambridge University Press

for the absolute magnitude at mean light. Clearly many more observations should be made to improve the determination of the apparent magnitudes at mean light and at typical maxima.

It is intended to publish the eight-color fluxes from the observations discussed here together with additional observations in 47 Tuc planned for a forthcoming run at Cerro Tololo. Observations of non-variable red giants as well as variables are planned.

B. ω CENTAURI (NGC 5139)

In contrast to 47 Tuc, ω Cen is metal-poor, contains well over 100 RR Lyrae stars, and has a relatively open structure so that measurements of individual stars in the central regions are much less affected by crowding. It also differs from 47 Tuc in having a very large radial velocity, making it possible to test the membership of any star quite definitely once a slit spectrogram is available. Color-magnitude diagrams have been published by Woolley (1966) and Geyer (1967).

Prior to 1970 no M-type stars were known to occur in this cluster apart from the Mira variable V2, which Feast (1965) has shown to have a grossly discordant radial velocity. On the other hand, ω Cen is the only globular cluster known to contain carbon stars; three of these have now been found (Harding, 1962; Stock and Wing, 1972; Dickens, 1972), and two of them have been confirmed as cluster members by radial velocity measurements. Although 11 slow variables have been found which are known from the photometry of Woolley (1966) to be redder than $B-V=1.30$, their spectra were largely unknown prior to this study and the work at Radcliffe Observatory (Dickens *et al.*, 1972; Feast, 1972, 1973). Several M-type spectra have now been found

TABLE II

Red variables in ω Centauri and NGC 362

Star	Period	Member-ship	Date	$I(104)$	θ	θ_0	T_0	Spectral type
ω Centauri								
V2	236^d	NM	'70 June 30	7.81:	1.45	1.33	3790 K	M2.8
			71 June 14	8.34	2.81	2.69	1870	M8.0:
V17	65	M	71 June 14	9.37	1.68	1.56	3230	M3.2
V42	149	M	71 June 18	8.52	1.50	1.38	3650	M0.0
V53	33 or 70	M	70 June 30	9.70:	1.50:	1.38:	3650:	< K5
			71 June 16	9.76	1.54:	1.42:	3550:	< K5
V138	75	?	70 July 1	9.32:	1.32:	1.20:	4200:	< K5
			71 June 18	9.23	1.37	1.25	4030	< K4
V148	90:	?	71 June 15	9.12	1.30	1.18	4270	⩽ K4.5 (str. CN?)
V152	irr.	M	70 July 1	8.68:	1.36	1.24	4060	< K5
			71 June 18	9.04	1.42	1.30	3880	⩽ K4
V164	irr.	M	70 July 1	9.39:	1.51	1.39	3630	< K5
			71 June 14	9.70	1.49	1.37	3680	⩽ K4 (str. CN?)
NGC 362								
V2	90	?	71 June 15	10.32	1.19	1.19	4240	⩽ K4.5

https://doi.org/10.1017/S0252921100033480 Published online by Cambridge University Press

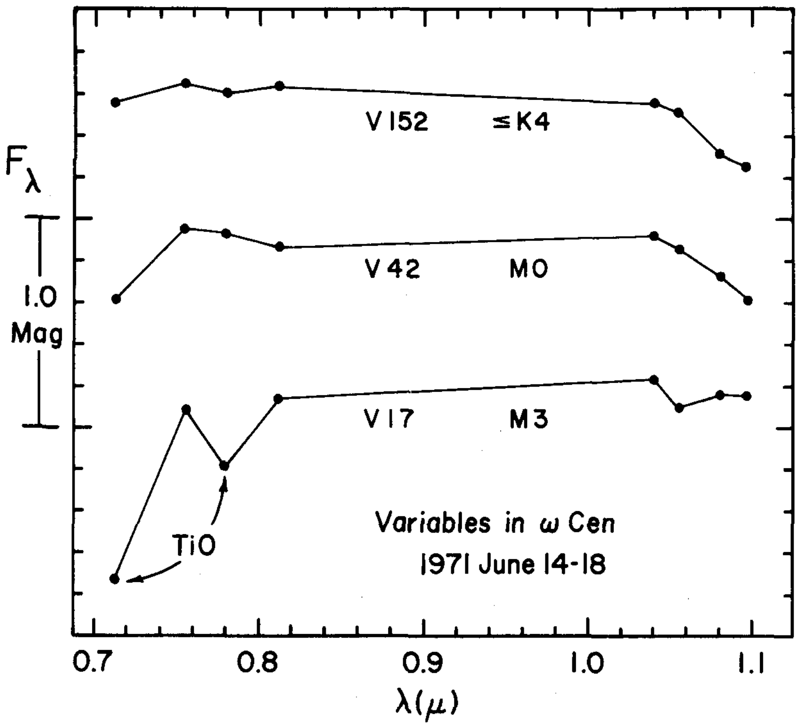

Fig. 3. Eight-color spectra of three small-range red variables in ω Cen. Different zero points are used for each star in this presentation; the actual $I(104)$ magnitudes are given in Table II.

among these variables. *UBVRI* photometry for some of them has recently been published by Eggen (1972).

Eight-color photometry was obtained in 1970 and 1971, again with the CTIO 60-in. telescope, for the Mira variable V2 and seven other red variables. Six of the latter were also observed by Dickens *et al.* (1972), and a comparison of our results is given in the concluding section of this paper. The observations are listed in Table II, which has the same arrangement as Table I except that a column has been added to indicate membership (M for member, NM for non-member) according to radial-velocity measurements (Feast, 1965; Dickens *et al.*, 1972). The $I(104)$ magnitudes measured on 1970 June 30 and July 1 are uncertain by about ± 0.05 mag. because of the flexure problem mentioned earlier and are therefore given with colons; the uncertainties are smaller here than in 47 Tuc because local standards were observed. The adopted interstellar reddening, following Wing and Stock (1973), is $E(B-V)=0.15$, corresponding to $\Delta\theta=0.12$, $A(V)=0.45$, and $A(104)=0.15$ mag.

Figure 3 shows the eight-color spectra of three of the red variables in ω Cen. V17 has strong TiO bands corresponding to type M3.2$\pm$0.2. The small apparent depression at filter 6 in this star is probably just the result of noise in the data, since the VO band does not normally appear until the TiO is much stronger. V42 also shows definite

https://doi.org/10.1017/S0252921100033480 Published online by Cambridge University Press

TiO absorption and is assigned type M0.0±0.3, which means a range of possible values from K5.7 to M0.3 since types K6–K9 do not exist on the scale employed.

V152 is shown as an example of a star having very weak or absent TiO bands. If the slight depression at filter 1 is real and due to TiO, the type is K4.0. It is also possible, however, that no TiO is present and the depression at filter 1 is due merely to a combination of observational scatter and weak CN absorption, in which case the type is earlier than K4.

The variables V53 and V138 show no evidence of TiO absorption, and only limits can be placed on their types. In the case of stars without TiO, earlier limits correspond to more accurate observations. In general, the 1971 data are of superior quality to the 1970 data.

The spectra of V148 and V164 have weak depressions at filter 1 that are believed to be real. If they are, there are two possible interpretations: (1) TiO is present, in amounts corresponding to types K4.5 and K4.0, respectively; or (2) TiO is absent and CN is abnormally strong, affecting filter 1. This second possibility is suggested by the depressions at filters 4 and 8, which are intended to measure CN. Choosing between these alternatives is simply a matter of securing further observations to reduce the observational scatter so that the level of CN absorption can be established from the measurements at filters 4 and 8, since then the contribution of CN to filter 1 would be known (see White, 1972). In view of the presence of carbon stars with much stronger CN bands in this cluster, it would be particularly interesting to confirm that stars with more modest CN enhancements also occur.

The two small-range variables showing definite TiO absorption, V17 and V42, have been plotted as crosses in Figure 2. We see that they have nearly normal band strengths for their colors, after corrections for reddening. Conversely, if we use Figure 2 to determine the reddening of ω Cen by assuming a normal relation between band strength and color (which may or may not be appropriate), the indicated reddening in $B-V$ is in the range 0.15 to 0.25 mag.

We may use the $I(104)$ magnitudes and the values of θ given in Table II to construct an infrared color-magnitude diagram that is essentially free of the effects of blanketing. This diagram will be shown in a subsequent paper (Wing, 1973) which will also include the complete eight-color photometry for stars observed in ω Cen, including 12 non-variable red giants defining the giant branch. Here we simply call attention to the fact that these variables scatter widely about the giant branch, even in a diagram that should closely approximate one of bolometric magnitude against effective temperature. At the time of these observations, the M3 star V17 was much cooler than any of the non-variables, while V42 was some 0.8 mag brighter than the tip of the giant branch. Of the non-TiO stars, V53 and V164 fall below the tip, while V138, V148, and V152 are brighter and warmer than the non-variables. The general locations of these stars are confirmed by the V,I photometry of Dickens *et al.* (1972), who also verified the cluster membership of most of them. Lloyd Evans and Menzies (1973) have also called attention to the existence, in other clusters, of stars that are brighter and bluer than the stars of the giant branch.

Finally, mention should be made of the Mira variable V2. Although Feast (1965) classified it as a 'normal Me variable', the present observations are the first, to my knowledge, to give spectral sub-types. The more advanced of the two types, M8.0:, was measured at $V \approx 16$ and is uncertain because it was necessary to include within the diaphragm a star that was brighter visually and that affected the TiO measurement at filter 1, where V2 was faintest; the classification is therefore based primarily on the VO strength at filter 6.

Since both the spectral range and the period (236^d) of V2 in ω Cen are rather similar to those of the Miras in 47 Tuc, it is surprising that its radial velocity (Feast, 1965) differs by more than 250 km s^{-1} from that of the cluster. Assuming $(m-M)_0 = 13.7$ (Eggen, 1972) and $A(104) = 0.15$ (Wing and Stock, 1973) for ω Cen, we find that if V2 lies at the same distance, then its infrared absolute magnitude, corresponding to the mean of the two observations, is $M(104) = -5.8$, in close agreement with the value -5.6 found above for the Miras in 47 Tuc. Therefore it seems likely that V2 does, in fact, lie at roughly the same distance as ω Cen, whether or not it is (or ever was) physically associated with it. Since the original velocity measurement was based on a single plate, it would be worthwhile to secure a second plate and repeat the measurement, and Dr Feast has indicated to me that he will make this observation at the next favorable opportunity.

C. NGC 362

A single observation of the 90^d variable V2, the only known slow variable in NGC 362, is listed in Table II. Although this cluster is quite small and compact, V2 is located far enough out from the center that crowding was not a problem. No definite TiO absorption was detected; the spectral type is not later than K4.5. The color temperature of 4240 K, assuming no reddening, suggests an early K spectral type.

Eggen (1972) has published *UBVRI* photometry for this star and several non-variables belonging to NGC 362. V2 lies at the tip of the giant branch, and its $R-I$ colors are consistent with a spectral range of roughly K2 to K4.5.

3. Summary and Final Remarks

The eight-color narrow-band photometry has proved to be a useful tool in studying the red variables in at least the brighter of the globular clusters. Although it would be worthwhile spending more time on each star to increase the accuracy of the data, the present observations, representing only about 20 min per star, have yielded (1) more accurate spectral types for the M stars than have previously been available, (2) CN indices which readily distinguish carbon stars and indicate that a range in CN strength probably exists among the K giants of ω Cen, (3) color temperatures that are unaffected by blanketing, and (4) an $I(104)$ magnitude measured in the infrared continuum, near the peak of the energy distributions of late K and early M stars. The chief reasons for wishing to improve the observational accuracy are to locate these stars more precisely in the infrared color-magnitude diagram and to make more subtle distinctions with regard to CN strength.

As Feast (1973) has mentioned, the Radcliffe image-tube spectrograms of globular cluster stars are being supplemented by wide-band infrared photometry in *I* and *K*. When the spectroscopic and photometric observations are combined, the Radcliffe data give essentially the same information as the eight-color system. The spectrograms, of course, give more spectroscopic information than the narrow-band photometry; in particular they furnish a radial velocity. The eight-color system, on the other hand, is capable of measuring weaker CN bands and is more convenient for an observer working alone, since all the data are obtained simultaneously.

Despite the many differences between 47 Tuc and ω Cen, they have been found to contain rather similar small-range variables of type M. No systematic difference in the relation between TiO strength and temperature (Figure 2) between the two clusters is evident. A meaningful comparison of the CN strengths of the K and M stars must await more precise observations. One difference between the clusters that the data of Tables I and II seem to indicate is in the spectral types of the non-Mira variables: both such stars observed in 47 Tuc are later than any of their counterparts in ω Cen. However, exactly the opposite conclusion was reached by Feast (1973) who found no types later than M3 in 47 Tuc whereas Dickens *et al.* (1972) classified two stars in ω Cen as M5. The differences are simply the result of not observing all of the same stars: the Radcliffe program did not include the two latest small-range variables in 47 Tuc, just as I missed the two latest stars in ω Cen. When all the data are considered together, we must conclude that the coolest non-Miras in the two clusters are quite similar, with spectral types near M5. For the stars observed in common, the eight-color and Radcliffe types are in excellent agreement. The type given here for V42 in ω Cen, M0.0, lies outside the range M1:e–M2.5e recorded by Dickens *et al.* (1972) but may easily be attributed to the variability of the star. Likewise the range in type found here for the Miras in 47 Tuc, M3.1–M7.5, is consistent with the types M2–3 given for all three by Feast and Thackeray (1960), since the earlier spectroscopic observations were restricted to phases near maximum light.

One lesson learned from the infrared photometry – both wide-band and narrow-band – is that stars which fall below the tip of the red giant branch in conventional color-magnitude diagrams (V vs $B-V$) should not be dismissed as foreground dwarfs on that basis alone. Some years ago, I pointed out (Wing, 1967a) that the extension of a cluster's red giant branch into the M types, if it exists, should be found directly below the tip since the appearance of TiO depresses the V magnitude while holding the B—V color constant throughout the range K5–M8. Several examples of such stars have recently been found: for example, V11 in 47 Tuc and V17 in ω Cen, considered non-members by Wildey (1961) and Eggen (1972), respectively, primarily on the basis of their faint V magnitudes, have both been found to have infrared magnitudes consistent with membership, and the latter star's membership is confirmed by its radial velocity (Dickens *et al.*, 1972). Several similar stars have been found by Lloyd Evans and Menzies (1973).

At the same time, there exist non-TiO variables which lie both above and below the giant branches of their clusters; since blanketing is not important in these stars, they have the same location relative to the giant branch no matter what kind of photometry is used. Good examples are R10 in 47 Tuc (above giant branch: Lloyd Evans and Menzies, 1973) and V164 in ω Cen (below giant branch: Eggen, 1972; Dickens *et al.*, 1972; Feast, 1973; and this paper). It will be an important theoretical problem to interpret the abnormal luminosities and variability of these stars.

It is to be hoped that spectroscopic work on very red stars in globular clusters will progress more rapidly now that several studies have shown them to be quite common. Direct photography in the infrared, such as Lloyd Evans and Menzies (1973) have described, is an efficient means of selecting stars for spectroscopic examination and should be applied to all globulars. A specific search for carbon and S-type stars in globular clusters should be made, and several techniques that might be used have been described by Wing and Stock (1973). Whereas the atomic spectra of heavy elements indicate the metallicity of the material from which the cluster formed, the molecular spectra of the red stars provide information about the relative abundances of carbon, nitrogen, and oxygen, and hence about the processes of nucleosynthesis and mixing that occur during the red giant stage of an individual star's life history.

Acknowledgements

It is a pleasure to acknowledge stimulating and useful discussions with Drs R. J. Dickens, M. W. Feast, T. Lloyd Evans, and J. W. Menzies, and to thank them for providing preprints of their work while this paper was being prepared. I am grateful to the Director of Cerro Tololo Inter-American Observatory, Dr V. M. Blanco, for the time on the 60-in. telescope that made these observations possible, and to the National Science Foundation for financial support.

References

Arp, H. C.: 1965, in A. Blaauw and M. Schmidt (eds.), *Galactic Structure*, University of Chicago Press, Chicago, p. 401.
Arp, H. C., Brueckel, F., and Lourens, J. v. B.: 1963, *Astrophys. J.* **137**, 228.
Dickens, R. J.: 1972, *Monthly Notices Roy. Astron. Soc.*, **159**, 7p..
Dickens, R. J., Feast, M. W., and Lloyd Evans, T.: 1972, *Monthly Notices Roy. Astron. Soc.*, **159**, 337.
Eggen, O. J.: 1961, *Roy. Observ. Bull.*, No. 29.
Eggen, O. J.: 1972, *Astrophys. J.* **172**, 639.
Feast, M. W.: 1965, *Observatory* **85**, 16.
Feast, M. W.: 1972, *Quart. J. Roy. Astron. Soc.* **13**, 191.
Feast, M. W.: 1973, in J. D. Fernie (ed.), *Variable Stars in Globular Clusters and in Related Systems*, D. Reidel Pub. Co., Dordrecht, Holland, p. 131.
Feast, M. W. and Thackeray, A. D.: 1960, *Monthly Notices Roy. Astron. Soc.* **120**, 463.
Fourcade, C. R., Laborde, J. R., and Albarracin, J.: 1966, *Atlas y Catálogo de Estrellas Variables en Cúmulos Globulares al Sur de* $-29°$, Córdoba.
Geyer, E. H.: 1967, *Z. Astrophys.* **66**, 16.
Harding, G. A.: 1962, *Observatory* **82**, 205.
Joy, A. H.: 1949, *Astrophys. J.* **110**, 105.

Lloyd Evans, T. and Menzies, J. W.: 1973, in J. D. Fernie (ed.), *Variable Stars in Globular Clusters and in Related Systems*, D. Reidel Pub. Co., Dordrecht, Holland, p. 151.
Lockwood, G. W.: 1972, *Astrophys. J. Suppl.* **24**, No. 209, 375.
Lockwood, G. W. and Wing, R. F.: 1971, *Astrophys. J.* **169**, 63.
Sawyer Hogg, H. B.: 1973, *Publ. David Dunlap Obs.* **3**, No.6, in press.
Spinrad, H. and Wing, R. F.: 1969, *Ann. Rev. Astron. Astrophys.* **7**, 249.
Stock, J. and Wing, R. F.: 1972, *Bull. Am. Astron. Soc.* **4**, 324.
Tifft, W. G.: 1963, *Monthly Notices Roy. Astron. Soc.* **126**, 209.
White, N. M.: 1972, in M. Hack (ed.), *Colloquium on Supergiant Stars*, Trieste, p. 160.
Wildey, R. L.: 1961, *Astrophys. J.* **133**, 430.
Wing, R. F.: 1967a, in M. Hack (ed.), *Colloquium on Late-Type Stars*, Trieste, p. 205.
Wing, R. F.: 1967b, Doctoral dissertation, University of California, Berkeley.
Wing, R. F.: 1971, in G. W. Lockwood and H. M. Dyck (eds.), *Proceedings of the Conference on Late-Type Stars*, Kitt Peak National Observatory Contribution No. 554, Tuscon, p. 145.
Wing, R. F.: 1973, in preparation.
Wing, R. F. and Keenan, P. C.: 1973, in preparation.
Wing, R. F. and Stock, J.: 1973, in press.
Wing, R. F., Warner, J. W., and Smith, M. G.: 1973, *Astrophys. J.*, **179**, 135.
Woolley, R. v. d. R.: 1966, *Roy. Observ. Ann.* No. 2.

DISCUSSION

Buscombe: What angular aperture of diaphragm was used in the integrated narrow-band photometry of 47 Tuc?

Wing: Circular diaphragms of 43″ and 68″ were used for 47 Tuc: thus only the central regions were included.

Feast: (1) I should make clear that the spectral types I gave for the Miras in 47 Tuc refer to maximum light – they get to much later types when below maximum.
(2) In view of your work I checked the velocity of V 2 ω Cen. It is definitely quite different from the cluster.

Walborn: The 'spectral types' to a tenth of a subclass may be telling us more about the observational accuracy of the photoelectric technique than about the classification accuracy, in view of possible additional contributors to the band strengths, such as abundance differences, for instance.

Wing: For bright stars, the photoelectric types are reproducible to a tenth of a subclass, but the intrinsic scatter in the TiO $-\theta$ relation shows that the types are not pure temperature indicators, as you say. The same is true, however, of the MK types of M giants, since they likewise are essentially based on absolute TiO band strength.