New Variable Stars in the Globular Cluster M4

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Introduction

It is well known that there are RR Lyrae type variable stars in globular clusters. They are located at the Horizontal Branch (HB) of the colour-magnitude (C-M) diagram and were originally divided into three subtypes – Bailey a, b and c, but later combined into two – RRab and RRc. All of them are pulsation variable stars; the RRab type stars pulsate in the fundamental mode, while RRc do so in the first overtone.

According to the average periods of RR Lyrae stars, globular clusters are divided into two groups – Oosterhoff I and II. Within each group, the average periods of the variable stars form a continuous distribution. The average period of RRab is about 0.55 and of RRc is 0.32 days for the Oosterhoff I class; the corresponding average periods are 0.65 and 0.37 days for Oosterhoff II. The globular cluster M 3 is a typical Oosterhoff I cluster and so is the globular cluster M 4. According to Sandage (*Ap. J.* **248,** 167, 1981), all the relations of period-colour (temperature), period-amplitude, etc. are the same in M3 and M4.

Early in the 1940's, Martin Schwarzschild found that the RR Lyrae stars in M3 are confined to a small compact region in the C-M diagram. He stated that for a star to vary, it is a necessary and sufficient condition that it has a colour index between CI = −0.005 and CI = +0.235 magnitude and an apparent, visual magnitude between 15.54 and 15.70, i. e. the physical conditions of a star must be rather specific for oscillations to occur.

It is very important to check how sharply the boundaries of this instability strip are defined; does pulsation stop entirely at a given point in the C-M diagram, or do variations of small amplitude persist on either side of the supposed limits of the strip? If this is the case, then an accurate determination of these boundaries would be very important for testing theoretical concepts as well as for practical purposes, e. g. for the estimate of interstellar reddening. As a matter of fact, Schwarzschild's results for M3 were subsequently confirmed and have also been supported by observations in other globular clusters.

This work was done already 32 years ago by Morton Roberts and Allan Sandage (*A. J.* **60,** 185, 1955). Using the Mount Wilson 100-inch reflector diaphragmed to 58″, they obtained 25 IIa-O + WG2 and 26 103a-D + GG11 plates (exposure time 15 minutes). 22 apparently nonvariable stars located at both sides of the instability strip and 47 variables within this strip were measured and the conclusion was that none of the stars outside the strip can be variable with amplitudes $A_{pg} \geq 0.07$. The colour boundaries of the instability region were found to be very sharp with colour indices corresponding to (B-V) = +0.20 and +0.45. All stars lying within the region are variable and no variable stars are found outside the region. Incidentally, the authors also found three small-amplitude variables with $A_{pg} \leq 0.15$; the periods have been determined for two of them. They are located on the red and blue boundaries of the instability strip, but not outside it.

M.F. Walker also made the same type of investigation (*A. J.* **60,** 197, 1955). He used the same telescope, but a photoelectric photometer with a photomultiplier plus a yellow filter. The two globular clusters M3 and M92 were observed; the latter belongs to the Oosterhoff II group. 12 stars were chosen in M3 and 17 stars in M92, and he concluded that "the boundaries of the gap are extremely sharp, and that beyond the edges of the gap, no light variations occur with ranges greater than 0.02 magnitude.

The Borders of the Instability Strip

B.V. Kukarkin, in his review "RR Lyrae and W Virginis type stars" (IAU Symposium No. 67, 522, 1975), wrote that it is necessary to undertake a careful investigation of the stars near the boundaries of the instability strip. Since the discovery of the two small-amplitude variables in M3 by Roberts and Sandage, nobody has investigated these stars to confirm or to disprove their results. Kukarkin also mentioned that in recent years Voroshilov at the Southern Station of the Sternberg Astronomical Institute discovered small-amplitude variable stars near the instability strip. Unfortunately, I have not yet seen these results.

I have thought about the apparent sharpness of the instability gap, ever since we began to observe the globular cluster M4 in 1975. While using M4 as a calibration cluster to measure our newly discovered flare stars and variable stars in the ϱ Oph dark cloud region, a group of unusual, suspected variable stars was found. When they were provisionally plotted in the C-M diagram, their potential importance immediately became apparent. We should have observed M3 and M92 first, but the exposure times would have been 8 times longer than for M4 to get the same photometric accuracy. Therefore, we had to observe the nearest cluster M4 with our small telescopes, in spite of the fact that its declination is −26°.5, and it could only be followed during 6 hours in a single night. Although we observed it frequently during the past ten years by photographic methods, we could not solve the problem completely until we used the new CCD Camera at the Yunnan Observatory and also had the opportunity to use ESO's advanced computer system and MIDAS.

Now, we ask the old question: Are there really no variable stars outside the instability strip determined by RRab and RRc type stars? We do not mean the microvariability; if you could obtain an accuracy better than 0.001 mag., most stars would probably appear to be variable. Here we ask the question from the

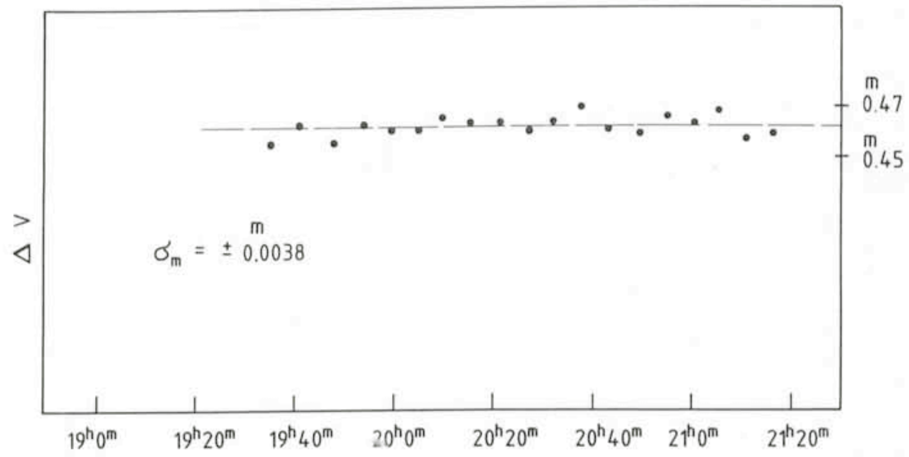

Figure 1: *Δ V between two constant stars on the night of 17 March 1986. Note the small r. m. s. value.*

Notes on the Use of DAOPHOT

DAOPHOT is one of the best programmes in the world for stellar photometry in crowded fields. Many people use it, and it can also be run within MIDAS at ESO. A detailed DAOPHOT User's Manual by P.B. Stetson is stored on-line (and is also available from F. Murtagh). He recently added some supplements (P.A.S.P., **99,** 191, 1987). Our aim was to do low-amplitude variable star photometry with an accuracy of 0.01 mag or better. While we have been successful in running DAOPHOT at ESO, the following notes may be useful for other DAOPHOT users. These notes refer to the "old" version of DAOPHOT at ESO.

(1) The shape of the Point Spread Function (PSF) may not be unique within the whole frame. The CCD we used belongs to those which have variable PSF across the frame. For isolated bright stars, the systematic error caused by using the PSF from the lower part of the frame in the upper part is less than 0.02 mag (not including the extreme corners). But for differential photometry, the Δm between the comparison and the variable star is less influenced by this kind of error.

(2) When the zenith distance was larger than 65°, even 60 seconds exposure was not long enough for 13^m stars to well establish the statistical properties of the seeing, and even stars located within a small area, say, 50 × 50 pixels, may have different shapes (PSF). This of course depends on the instrumentation used and also the seeing. Using different "CUTS" (one value to indicate the halo of the stars and the other to indicate the core) one can clearly see the difference of the shapes on the DeAnza screen.

(3) For poorly guided frames, the star images are irregular and the use of an inaccurate PSF may lead to disaster. We have encountered the case where after subtracting the bright stars from the original frame and then running the "FIND" routine again, the residuals of some bright stars were detected as *false* faint stars together with the *real* faint stars buried in the profiles of bright stars (sometimes the real faint stars were omitted). If these false faint stars were not deleted manually from the list when running the "NSTAR" routine, decidedly wrong results would be obtained. Checking the CHI value was no use at all in this case, because it was not worse than that of the nearby real faint stars. Somebody who is not familiar with his star field must be very careful.

(4) Even at the step of "GROUP", strong interactive operation is necessary. This automatic routine divides the star list for a given frame into optimal subgroups in order to reduce the CPU time and to describe the sky brightness with fewer parameters. For the version we used, the criterion to divide stars into subgroups is a critical separation, which is the sum of the brightest star image radius and the fitting radius. For the version used at DAO, the critical separation is a function of apparent magnitude. The stars within one subgroup are close enough so that the light of one will influence the profile-fitting of another and they should be reduced together. For the version of DAOPHOT now released, the maximum number of stars run by the "NSTAR" routine is 60.

The problems we have met in practice are:

(a) In our frames sometimes the stars in one subgroup form a long, thin and curved string over a large area. We do not think it is suitable to consider the stars of this long string as one unit which have the same PSF. It is also not good to break them into smaller subgroups by using a smaller critical separation value. We prefer to load the star list given by the "GROUP" routine onto the DeAnza screen and "EDIT" the stars manually, i.e. to find some star(s) on the string where it is relatively sparse, break the string over at this point and so group the stars in this way.

(b) Sometimes it happened that the stars which belong to one group are really located within a compact region and should be reduced as a unit, but the number is a little larger than 60. According to DAOPHOT, the "SELECT" routine must be used to select a slightly smaller critical separation value and break this group into several smaller subgroups. Unfortunately, it often happened that among these subgroups many stars were divided into one star per subgroup. For these "single" stars, the "NSTAR" routine became the "PEAK" routine, i.e. the multiple simultaneous profile-fitting advantage was lost. In this case, we simply edited the group file and took away some stars at the edge of the group on the screen, considering them as another small subgroup and sacrificing their accuracy. Now the original group contained less than 60 stars and could be run with "NSTAR".

(5) One must be very careful while running the "PSF" routine in a crowded field. In the DAOPHOT Users' Manual, Stetson vividly describes the process as an art, not a science. Obtaining a good PSF in a crowded field is a delicate business; do not expect to do it quickly, plan on spending a couple of hours for this endeavour.

The author of this article will be happy to directly inform interested persons about his experience with DAOPHOT in greater detail than is possible here.

classical viewpoint: are there any variables outside the strip with amplitudes larger than 0.02 mag.?

Observations

An RCA thinned back-illuminated 320 × 512 pixel CCD (pixel size 30 × 30 μm) mounted at the 1-metre reflector (f/13.5) of the Yunnan Observatory in Kunming, P.R. China, was used to observe M4 during 8 nights in March and May of 1986. A series of successive frames was obtained during each night with a typical exposure time of 5 minutes through the V filter and each star was nearly fixed at the same position of the frame. As mentioned above, the zenith distance of M4 is always large for northern observers.

The data reduced at ESO were obtained on May 11, 1986 and consist of

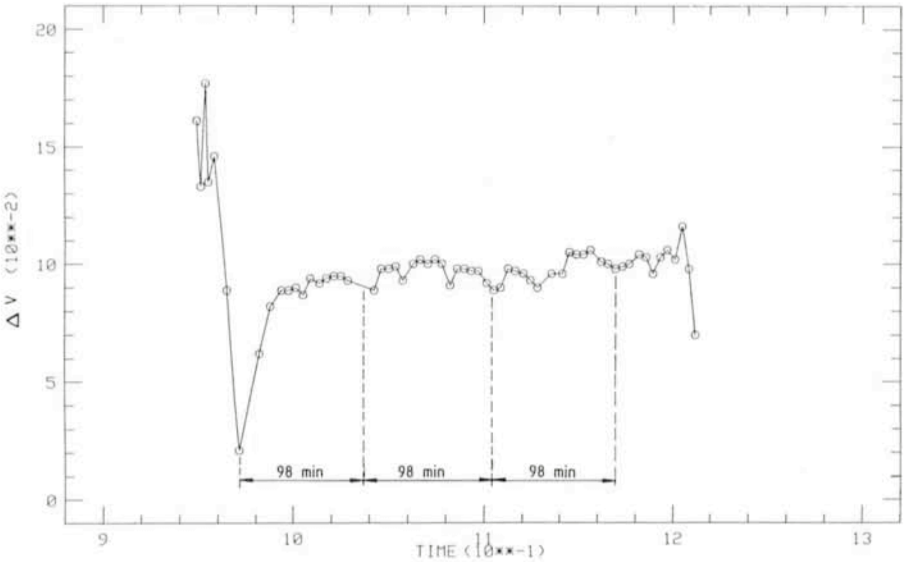

Figure 2: *Δ V (G266–G265) with some apparent minima, separated by 98 minutes. Magnitudes in this and the following figures are in units of 0.01 mag. Time is in units of 0.1 day.*

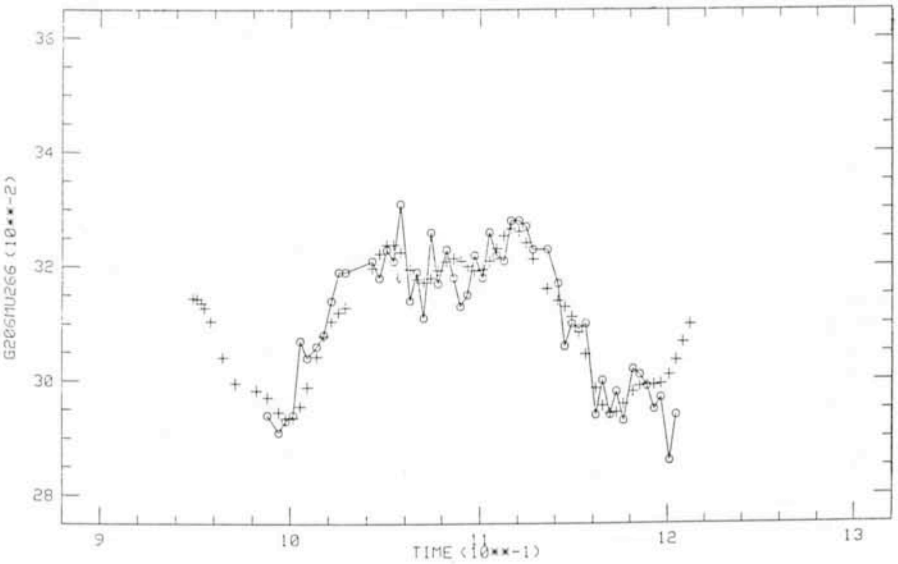

Figure 3: *Δ V (G206–G266). In Figures 3–5, crosses are observations and circles indicate a composite curve of sine functions, obtained by a straightforward fit to the observations and not necessarily with any physical meaning.*

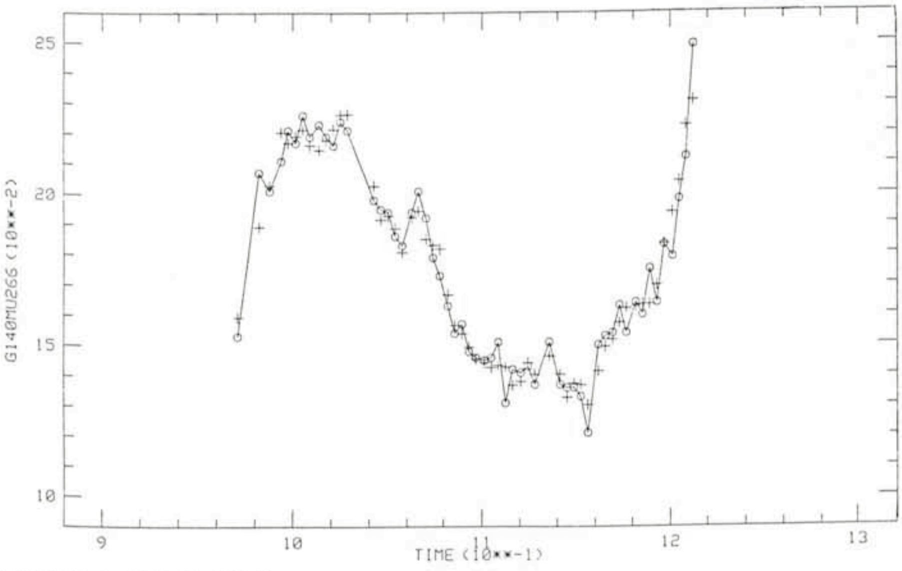

Figure 4: *Δ V (G 140–G266).*

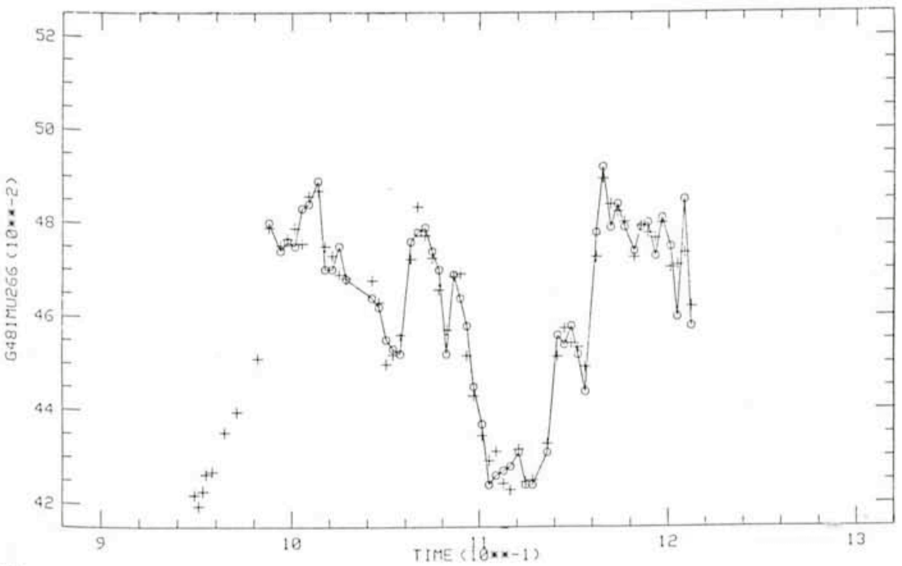

Figure 5: *Δ V (G481–G266).*

62 frames with zenith distances from 71° to 51°.5 (meridian) and then to 66°. But the signal-to-noise ratio is still good, and the typical intensity accumulated by the CCD is about 10^5 ADU for a V = 13 star exposed for 5 minutes. Entering this ADU value and other parameters such as readout noise into the formula, the calculated standard error is about ± 0.002 mag., the accuracy of the magnitude difference between two V = 13 stars is about $\sqrt{2} \times 0.002 = \pm 0.003$ mag.

We almost reach this accuracy in practice. It is generally believed that the current accuracy of CCD photometry, even in a sparse star field, is 0.01 magnitude or worse, due to the limitations mentioned in Stetson's paper about DAOPHOT. However, differential photometry is always better. Since we exposed in such a way that every star occupied approximately the same pixels in all frames, and since we chose a comparison star with a colour similar to that of the variable star, we can obtain more accurate results. For example, Figure 1 represents the magnitude difference between two stars (V = 12.7 and V = 13.3), observed on March 17th and reduced by a running aperture photometry routine (APERASP in STARLINE) at the Beijing Observatory. Here $\sigma = 0.0038$ mag.

We decided to use DAOPHOT (see also the box), because we wanted to identify any faint nearby stars embedded in the wings of the bright variables and to eliminate them in order to improve the accuracy.

Unusual Variable Stars in M 4

The main purpose of the present study was to confirm the previous observations of variability which were made by photographic methods. With our small telescopes only the outer part of the cluster could be investigated so among the five variable stars discussed here, only three have faint stars embedded in their wings with influences ≤ 0.01 mag. The other stars have no detected blended stars, so for them the accuracy is more or less similar to that of aperture photometry. The V and (B-V) values from the literature are listed in the Table and their positions in the C-M diagram of M 4 are shown in Figure 7.

Well aware that it is not possible to determine accurate periods on the basis of observations from only one night reduced so far, we have used all the three methods of time series analysis available in MIDAS (PDM, SVM, DFT) to make a provisional search for periods; they give similar results. There is little doubt that the stars are variable, but as shown below, the light curves are com-

Data for 5 Variable Stars in M4

Star	V		(B-V)	
	Alcaíno	Lee	Alcaíno	Lee
G265 = A375 = L4508	12.9		1.3	
G206 = A491 = L4632	13.50	13.43	0.28	0.45
G140 = A488 = L3602	13.33	13.22	0.36	0.49
G481 = A371 = L4512	13.45	13.41	0.87	0.90
G543 = A376 = L4507	13.46	13.46	1.29	1.27

Alcaíno (ref. 2). Lee (ref. 3).

plicated, similar to those of Population I δ Sct stars. It might therefore be useful to organize some international cooperation in the future, in order to analyse the periods in these light curves.

(a) *A variable star with periodicity in the middle part of the Red Giant Branch*

G 265 = Alcaíno 375 = Lee 4508 (refs. 1–3) is a red giant star, about 3.3 arcmin from the centre of the cluster (see the map in ref. 2). All the authors put it slightly below the middle part of the Red Giant Branch. Norris (ref. 4) determined its radial velocity (62 km/s) and showed that it is a cluster member.

Using G 266 as comparison star, the resulting light curve is shown in Figure 2. It may be compared with the curves in our previous paper (refs. 5, 6). Apart from the irregular variations superimposed on the curve, the period P = 98 min. is possibly real. In Figure 2 and in the earlier photographic curves (refs. 5, 6) there are several minima which are separated by this interval. In Figure 2, from U.T. 15^h50^m (corresponding to the ninth point from left) to 20^h50^m, the amplitude is only 0.02 mag., but the accuracy is so good that a 0.01 mag. variation is significant.

If the 98-min. period is confirmed when more nights have been reduced, it may be assumed that it has a cause other than pulsation, e.g. rotation and/or binary. Huge star spots may also persist for some time on the surface.

(b) *RRe – another subgroup of RR Lyrae stars in globular clusters?*

Here some data are given about 3 variable stars; the light curves are shown in Figs. 3, 4 and 5. Their positions can be seen in the map in ref. 2, and they are identified in the C-M diagram of Lee (ref. 3) in Figure 7.

G206 = Alcaíno 491 = Lee 4632 is located on the blue side of the HB and has a nearby faint star separated by 3.3 pixels (1.6 arcsec). The influence is ~ 0.01 mag. if this 4.2 mag. fainter star is not subtracted. A possible period is P 1 = 0.205 days and the total amplitude is 0.04 mag in V.

G 140 = Alcaíno 488 = Lee 3602 is located on the blue side of the HB: it has 3 nearby faint stars. Their angular distances and the brightness differences from G 140 are: 10.9 pixels, 4.6 mag.; 6.5 pixels, 3.5 mag.; 5.9 pixels, 3.7 mag. The combined influence of these is ~ 0.01 mag. The main period appears to be P 1 = 0.216 days with amplitude 0.043 mag. The total amplitude is 0.1 mag. in V.

G 481 = Alcaíno 371 = Lee 4512 is located on the red side of the HB. No nearby faint stars have been found, so its results are more accurate than the others. However, in some frames, the star was exposed near the edge. A possible period is P1 = 0.167 days and the total amplitude is 0.07 mag. in V.

According to stellar statistics at galactic latitude 16°, there should be

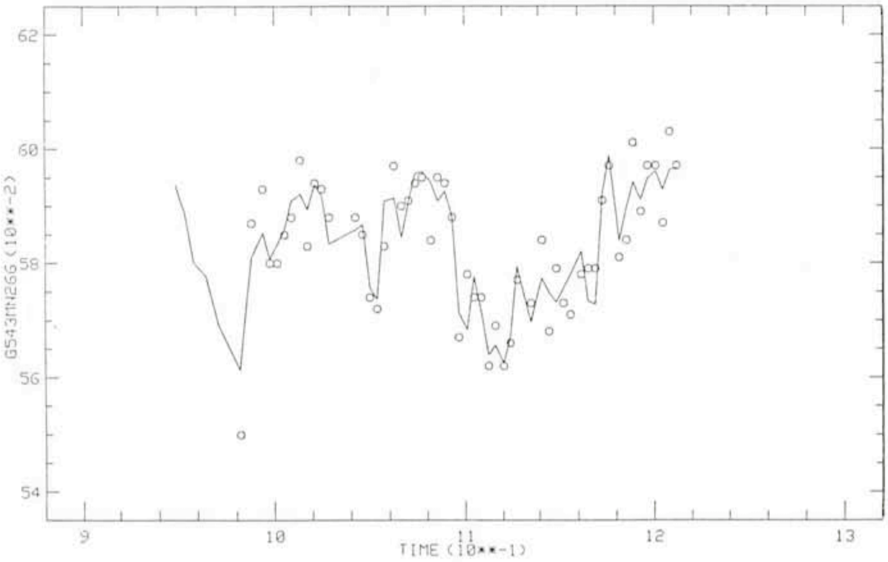

Figure 6: *Δ V (G543–G266). The observations are indicated with open circles.*

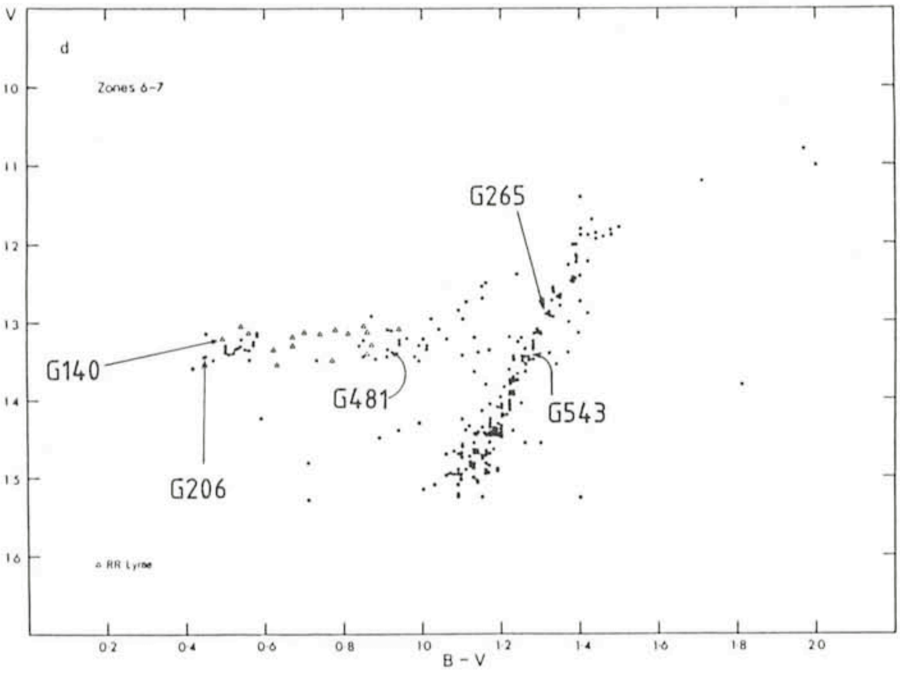

Figure 7: *Colour-Magnitude diagram of M4 from Lee (ref. 3), with the new variable stars indicated.*

3.5 field stars with $m_{pg} < 14.5$ mag. within an area with radius 3.6 arcmin., so it is unlikely that these variable stars all belong to the field. Furthermore, the star G 327 (V = 13.28, B-V = 0.35; ref. 5) is also located at the blue side of the HB, and at least 5 unpublished, similar stars are waiting for checking.

A provisional conclusion is that these stars may form a new group. For the time being we call them "RRe" and maybe they should be divided into two: one on the blue side and the other on the red side of the classical boundaries of the instability strip.

(c) A Variable Star at the HB/RGB Intersection

G 543 = Alcaíno 376 = Lee 4507 has a nearby faint star separated by 4.2 pixels (1.9 arcsec) with brightness difference about 3.6 mag. The influence of the faint star is ≤ 0.01 mag., but the influence varies with seeing and guiding. The light curve is complicated and the time interval is not long enough for it to be analysed. This would be the first known variable at the intersection of the HB and RGB.

I hope that these results, albeit provisional, will stimulate similar research in other places and that more astronomers will become interested in pointing their large telescopes at globular clusters in the future.

Acknowledgements

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Neutron Density and Neutron Source Determination in Barium Stars

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Introduction

The origin of the large s-process enhancements observed in the classical Barium (Ba II) stars (Lambert 1985) remains one of the most fundamental challenges in stellar nucleosynthesis theory. An understanding of this phenomenon would lead to an improvement in our knowledge of both s-process systematics, and mixing processes occurring during the late phases of stellar evolution. A determination of two crucial aspects of the s-process site, namely the neutron source and the neutron density, would be a significant advance towards this goal. Knowledge of these two parameters would allow strong constraints to be placed on any evolutionary hypothesis purporting to explain the Ba II star phenomenon. Hitherto, the neutron source has been analysed in only two Ba II stars, and the neutron density also in only two.

In order to extend such studies to other members of this important stellar class, spectroscopic observations of a large number of both northern and southern hemisphere Ba II stars were obtained. This work was carried out in collaboration with D.L. Lambert at the University of Texas, Austin. In this paper, which reports the first results of our survey, we discuss the determination of the neutron source and neutron density in the cool (K4) Ba II star HD 178717, and compare our results with the abundances predicted if mass transfer from an evolved asymptotic giant branch (AGB) star has occurred. This scenario for the origin of the s-process enhancements in Ba II stars has received a great deal of theoretical and observational attention in recent years (see Malaney 1987).

Observations of Neutron Indicators

The two most likely neutron producing reactions in a stellar interior are the $^{13}C(\alpha, n)^{16}O$ and the $^{22}Ne(\alpha, n)^{25}Mg$ reactions. It is well known that the operation of the $^{22}Ne(\alpha, n)^{25}Mg$ neutron source should lead to an observable distortion in the relative abundances of the magnesium isotopes from their solar system distribution of $^{24}Mg : {}^{25}Mg : {}^{26}Mg = 79 : 10 : 11$. In order to obtain information on the source of neutrons, the magnesium isotopic mixture in HD 178717 was determined from observations of the molecular MgH (0,0) band lines at 5101 Å and 5107 Å. The MgH lines at 5101 Å have the advantage of a large isotopic splitting (~0.14 Å). Contamination by lines from the C_2(0,0) and C_2(1,1) bands, however, leads to significant blending in this spectral region. Although the MgH lines at 5107 Å have the disadvantage of a smaller separation (~0.1 Å), the ^{25}MgH and ^{26}MgH lines are unaffected by C_2 blends. In addition, since the observed rubidium abundance is known to be an indicator of the neutron density at the s-process site, the abundance of this element in HD 178717 was determined from observations of the Rb I line at 7800 Å. In order to minimize non-LTE effects, this rubidium abundance determination was carried out differentially with respect to the standard K3 giant μ Aql.

The observations discussed here were obtained in April 1987 at the ESO La Silla observatory using the Reticon-equipped echelle spectrometer of the 1.4-m Coudé Auxiliary Telescope. The length and the resolution of the spectra were 40 Å and 0.05 Å, respectively, for the 5100 Å centred spectrum, and 60 Å and 0.08 Å, respectively, for the 7800 Å centred spectra. The signal-to-noise ratio in the continuum exceeded 100 in all of the obtained spectra. The raw data were reduced at Caltech using the spectral reduction package FIGARO.

In order to determine the magnesium isotopic distribution and the rubidium abundance of our stars, the observed spectra were compared with synthetic spectra calculated using an LTE spectral synthesis programme (Sneden 1974; assistance in the use of this code was provided by A. McWilliam). The required input for the synthesis programme, namely the parameters of the observed lines and atmospheric parameters of the observed stars had previously been determined. To allow a proper comparison of the theoretical and observed spectra, a composite of the rotational, macroturbulent and instru-