RR Lyrae variables in M5 as a test of pulsational theory

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ABSTRACT
We present B and V CCD photometry for variables in the cluster central region, adding new data for 32 variables and giving suitable light curves, mean magnitudes and corrected colours for 17 RR Lyrae variables. Adding the data given in this paper to similar data that have already appeared in the literature, we discuss a sample of 42 variables, as given by 22 RRab and 20 RRc, in the light of recent predictions from pulsational theories. We find that the observational evidence concerning M5 pulsators appears in marginal disagreement with predictions concerning the colour of the first overtone blue edge (FOBE), whereas a clear disagreement appears between the zero-age horizontal branch (ZAHB) luminosities predicted through evolutionary and pulsational theories.

Key words: stars: horizontal branch – stars: variables: other – globular clusters: general – globular clusters: individual: M5 – distance scale.

1 INTRODUCTION
After about a century of investigation, the precise and detailed knowledge of structural parameters of RR Lyrae variables in Galactic globular clusters is still a relevant target for stellar astrophysics. As a matter of fact, the true luminosity of these variables is still under debate (see, e.g., Gratton 1997, Caputo 1997, Cacciari 1999, and references therein), vis-à-vis the tantalizing evidence that improved knowledge of such an evolutionary parameter would produce firm constraints on several relevant issues, such as the distance of the parent clusters and – in turn – the distance to the Magellanic Clouds, which is a keystone for assessing a reliable distance scale in the Universe. In this context, observational data for these variables have become even more interesting, because we are now facing rather detailed scenarios of theoretical evolutionary and pulsational predictions which obviously require to be tested with observations.

In a previous paper (Brocato, Castellani & Ripepi 1996, hereinafter BCR96) we have already presented new light curves for 15 RR Lyrae stars in M5, pointing out the occurrence of several further pulsators in the crowded core of the cluster. In this paper we present data for these variables in the cluster central region, adding new data for 32 variables and giving suitable light curves and mean magnitudes for 17 RR Lyraes. The next section will present the explored fields, discussing the existing literature on M5 variables to give suitable cross-correlations between the nomenclatures adopted by different authors and advancing a proposal for homogeneous cataloguing for these variables. The new data will be discussed in Section 3. The final section will discuss available data for M5 variables in the light of recent predictions from pulsational theories. A brief conclusion will close the paper.

2 RR LYRAE VARIABLES IN THE M5 CENTRAL REGION
Observational material was secured in 1989 April with the 1.54-m ‘Danish’ telescope at ESO (La Silla, Chile), equipped with a RCA CCD of 331 × 512 pixels. For details regarding observations, calibration and the reduction procedure the reader is referred to BCR96. Fig. 1 shows the four explored frames, giving the identification map for the variables we will discuss in this paper. However, the nomenclature of the variables still needs to be discussed here in some detail.

As early as 1973, the Sawyer Hogg catalogue was already listing 103 variables in M5, with 93 RR Lyraes. Since that time several further pulsators have been found, mainly in the crowded central region. However, the contemporaneous publication of several papers dedicated to these variables has produced some overlap in their identification and nomenclature, worth discussing and clarifying.

In BCR96 we presented 26 new cluster RR Lyrae variables, which were added to the Sawyer Hogg list, from V104 to V129. However, we have now found that V124 was already marked as V102 in the Sawyer Hogg list, and 22 out of these 26 variables appear in the list by Evstigneeva et al. (1995, hereafter ESST), who added 30 new variables to the Sawyer Hogg catalogue (from V104 to V133), collecting data from Kadla et al. (1987, hereafter KGY1) and Kravtsov (1988, 1990, 1991, 1992; hereafter K88,
Figure 1. Identification maps for the variables in the core of M5.
RR Lyraes in M5

Figure 1 – continued
K90, K91, K92). In this series of papers one can find positions and finding charts for the 30 new variables near the cluster core, together with indications about periods and rather scattered light curves from photographic $B$ photometry. In the present investigation we tested four out of the eight stars in that list not in common with BCR96. Of the remaining four, V122, 126 and V127 were not detected because of crowding, while V133 lies outside our fields. We confirm the variability for three out of the

Figure 2. Light curves for all variable stars in our fields.
four objects, the exception being V124, which does not show magnitude variations within 0.1 mag.

More recently, Reid (1996, hereafter R96) has published an extensive $V, I$ survey of RR Lyrae variables in M5, reporting light curves and mean magnitudes for 49 RR Lyraes, 44 from the Sawyer Hogg list and five which belong to the Evstigneeva extension. In addition, R96 lists several RR Lyrae candidates in the cluster central region (see table 5 in R96). We tested for variability all these candidates, detecting variability only in star 315, which appears to be a RR Lyrae variable. Moreover, both R96

Figure 2 – continued

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and Yan & Reid (1996, hereafter YR96) discovered several eclipsing binaries in the cluster field, all outside our explored region. In the meantime, Sandquist et al. (1996, hereafter SBSH) reported the discovery of eight new variables, which were added to the list of ESST with numbers from V134 to V141. No period was given. From our observations it appears that V134 was already named as V129 in ESST, V135 is a new RR, V137 is the star V118 in BCR96, and V139 is the star 315 in R96, whereas we
were not able to detect variability in V136 nor in V140 and V144. We can say nothing about V138 and V141 because the former is saturated and the latter lies out of our fields. Finally, on the basis of F36W filter HST observations, Drissen & Shara (1998, hereafter DS) have recently given light curves for 29 variables in the core of M5, including five new variables. Because of crowding, we were able to detect only one of these variables, which appears to be a RR Lyrae pulsator.

As a whole, one finds that the literature on M5 variables would greatly benefit from a reorganization of the above discussed observations. Table 1 summarizes the situation, giving in the first column our adopted nomenclature, which runs as follows. From V104 to V133 we follow the notation of ESST, from V134 to V141 the classification by SBSH, with V142 to V158 denoting further variables from various authors. The next columns give the cross-identifications for all the variables in M5 not in the Sawyer Hogg (1973) catalogue, together with the source of the variable identifications. The last four columns give details for stars in the field of the present investigation or, for objects outside our fields, we give within brackets the original classification of the objects.

According to the data summarized in Table 1, one finds that out of 44 objects nominally present in our field, V134 is a duplicated nomenclature, in four cases (V124, V136, V140 and V144) we failed to detect luminosity variations, seven objects are in a too-crowded region and, finally, the image of a further object appears saturated. This paper will deal with the data for the remaining 31 variables plus V103 which falls in the investigated fields. The first column in Table 2 gives the list of these objects.

2.1 Light curves and notes on individual variables

In order to obtain light curves for the observed variables, we searched for periods by using a standard discrete Fourier decomposition (Deeming 1975; Kurtz 1985). However, in some cases the restricted time allowed for the observations caused the occurrence of too few phase points along the pulsational cycle. In that case we adopted periods from the literature. Data on periods, epochs of maximum, $B$ and $V$ amplitudes are reported in the same Table 2, together with the period source for each variable. Light curves for all variables listed in Table 2 are shown in Fig. 2. HJD and $BV$ magnitudes will be available via anonymous ftp at the address ftp.na.astro.it (pub/M5RR) or upon request by e-mail.

From the sample of RR Lyrae variables in Table 2 we selected the 17 objects with the best light curves, allowing a suitable estimate of mean magnitudes and colours. For this purpose, data
for the selected objects have been best-fitted with a spline function and then integrated over the fitted curve to find mean quantities by averaging (i) over the magnitude curve and (ii) over the intensity curve. The results of this procedure are reported in Table 3, where individual columns give (1) variable name, (2) period in days, (3) magnitude-averaged and (4) intensity-averaged \( V \); (5) magnitude-averaged and (6) intensity-averaged \( B - V \); (7) corrected \( B - V \) colours following Bono, Caputo & Stellingwerf (1995, hereafter BCS) prescriptions; (8) visual and (9) blue amplitudes.

As discussed by BCS, \( V \) appears to be a good indicator for the magnitude of the `static star', whereas the observed averaged colours need to be corrected in order to give the `static' colour. The consistency of BCS corrections is displayed in Fig. 3, where the upper panel shows the comparison between observed

Table 1. Cross-identification for variable stars not included in the Sawyer Hogg (1973) catalogue. The column `Source' gives the reference for the first identification of the object. The last four columns give details of the present investigation, where \( X \) and \( Y \) are the coordinates in pixels with respect to our reference frame.

| Ident. | Ident. | Ident. | Ident. | Source | \( X \) | \( Y \) | Field | Notes |
|--------|--------|--------|--------|--------|--------|--------|-------|-------|
| V104   | V114   | 333    | HST-V1 | KGYI   | 263.5  | 544.5  | F4    | ecl.? |
| V105   | V113   | 18     | HST-V10| K88,KGYI| 256.9  | 486.4  | F3    | RR Lyrae |
| V106   | V112   | 17     | HST-V14| K88,KGYI| 255.7  | 473.4  | F3    | RR Lyrae |
| V107   | V111   | 14     | HST-V24| K88,KGYI| 245.3  | 444.4  | F3    | RR Lyrae |
| V108   | V110   | 13     | HST-V22| K88,KGYI| 224.7  | 446.5  | F3    | RR Lyrae |
| V109   | V108   | 7      | HST-V20| K88,KGYI| 202.7  | 454.7  | F3    | RR Lyrae |
| V110   | V107   | 6      |        | K88,KGYI| 192.5  | 443.7  | F3    | RR Lyrae |
| V111   | V121   | 10     |        | K88,KGYI| 192.3  | 486.2  | F3    | RR Lyrae |
| V112   | V106   | 3      |        | K88,KGYI| 185.1  | 382.6  | F3    | RR Lyrae |
| V113   | V105   | 4      |        | K88,KGYI| 184.7  | 378.0  | F3    | RR Lyrae |
| V114   | V104   | 5      |        | K88,KGYI| 180.7  | 445.2  | F3    | RR Lyrae |
| V115   | V117   | 1      |        | K88    | 145.6  | 460.9  | F3    | RR Lyrae |
| V116   | V119   | 2      | 229    | K88    | 145.6  | 444.5  | F3    | RR Lyrae |
| V117   | V120   | 8      |        | K88    | 191.7  | 457.8  | F3    | RR Lyrae |
| V118   | V122   | 9      | HST-V18| K88    | 201.7  | 468.2  | F3    | RR Lyrae |
| V119   | V109   | 11     | HST-V11| K88    | 216.8  | 485.2  | F3    | RR Lyrae |
| V120   | V125   | 12     | HST-V17| K88    | 226.6  | 469.3  | F3    | RR Lyrae |
| V121   | V127   | 15     | HST-V26| K88    | 255.1  | 437.3  | F3    | RR Lyrae |
| V122   | 16     |        | HST-V23| K88    |        |        | F3    | crowded |
| V123   | V126   | 19     | HST-V5 | K88    | 244.7  | 515.0  | F4    | RR Lyrae |
| V124   | 20     |        | K88    | 265.8  | 518.0  | F4    | constant? |
| V125   | V128   | 21     | HST-V9 | K88    | 280.0  | 489.4  | F3    | RR Lyrae |
| V126   | 22     |        | HST-V12| K88    |        |        | F3    | crowded |
| V127   | 23     |        | HST-V13| K88    |        |        | F3    | crowded |
| V128   | V129   | 24     | HST-V25| K88    | 323.9  | 437.0  | F3    | RR Lyrae |
| V129   | 25     |        | K88    | 348.3  | 348.9  | F2    | RR Lyrae |
| V130   | V115   | 26     | 365    | K88    | 72.7   | 570.7  | F4    | RR Lyrae |
| V131   | 27     | 369    | K88    | 72.3   | 565.4  | F4    | RR Lyrae |
| V132   |        | K91    | 147.3  | 547.4  | F2    | RR Lyrae |
| V133   | 612    |        | K91    |        | (RR Lyrae) |  & VI29 |
| V134   |        | SBSH   | 83.8   | 348.9  | F2    | RR Lyrae |
| V135   |        | SBSH   | 265.9  | 341.1  | F3    | RR Lyrae |
| V136   |        | SBSH   | 197.2  | 273.9  | F3    | constant? |
| V137   | V118   |        | SBSH   | 145.5  | 536.5  | F4    | RR Lyrae |
| V138   |        | SBSH   | 66.4   | 114.4  | F1    | saturated |
| V139   | 315    |        | SBSH   | 281    | 64.4   | F4    | RR Lyrae |
| V140   |        | SBSH   | 150.8  | 504.6  | F3    | constant? |
| V141   |        | SBSH   |        |        |       |       |       | type? |
| V142   | V123   |        | HST-V21| BCR96  | 205.1  | 453.6  | F3    | RR Lyrae |
| V143   | V116   |        | BCR96  | 138.8  | 462.4  | F3    | type? |
| V144   |        | 596    | R96    | 287.9  | 551.8  | F4    | constant? |
| V145   |        | 629    | R96    |        |       |       |       | (ecl.) |
| V146   |        | 648    | R96    |        |       |       |       | (ecl.) |
| V147   |        | 651    | R96    |        |       |       |       | (ecl.) |
| V148   |        | 652    | R96    |        |       |       |       | (ecl.) |
| V149   |        | V1     | YR96   |        |       |       |       | (ecl.) |
| V150   |        | V2     | YR96   |        |       |       |       | (ecl.) |
| V151   |        | V3     | YR96   |        |       |       |       | (ecl.) |
| V152   |        | V4     | YR96   |        |       |       |       | (ecl.) |
| V153   |        | V5     | YR96   |        |       |       |       | (ecl.) |
| V154   |        | V6     | YR96   |        |       |       |       | (ecl.) |
| V155   |        |        | HST-V6 | DS     |        | F4    | crowded |
| V156   |        |        | HST-V15| DS     |        | F3    | crowded |
| V157   |        |        | HST-V16| DS     |        | F3    | crowded |
| V158   |        |        | HST-V19| DS     | 258.6  | 454.6  | F3    | RR Lyrae |
| V159   |        |        | HST-V28| DS     |        | F3    | crowded |

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RR Lyraes in M5

The light curve of R96 shows both an eclipsing binary like and an RR Lyrae like shape, and our conclusion is that the nature of V104 remains a mystery, deserving more observations.

V105: the star shows a visual magnitude significantly fainter (−0.3 mag) than other RR mean magnitudes, with a colour \((B - V) \approx 0.20\) in agreement with the blue edge of the instability strip. Possibly a foreground variable.

V113: this star shows a colour that is significantly bluer than the blue edge for first-overtone pulsation but a visual magnitude in agreement with the average luminosity of the other variables. This
V143: from the HJD versus magnitude plot (see Fig. 2) this star appears clearly variable even though we were unable to find any periodicity. Thus the nature of this star also remains uncertain.

Our complete sample (this paper + BCR96) contains 11 RR Lyres in common with R96, namely, in R96 notation, V36, V45, V81, V82, V97 (ab-type variables) and V35, V57, V78, V100, V116, V131 (c-type variables). Fig. 4 compares (V) and A(V) for these common objects.

From the upper panel of the figure one finds that our observations appear on average fainter in (V) by only ~0.03 mag. For visual amplitudes (lower panel) we have similar results, with the remarkable exception of V97. However, a simple inspection of the R96 light curve for V97 reveals that this star shows a Blazhko effect, as do many others in this sample.

Adding the data given in this paper to similar data already presented in BCR96 and to the B,V photometry given by Storm, Carney & Beck (1991, hereafter SCB) for 11 RR Lyre in the cluster periphery, we are eventually dealing with reliable light curves for a sample of 42 variables, as given by 22 RR_ab and 20 RR_c. This sample, with the high occurrence of core RR Lyrae variables, appears abnormally rich in c-type pulsators, with the ratio N_c/N_ab ~ 0.5 compared with the value of 0.26 found from the Sawyer Hogg catalogue (see, e.g., Castellani & Quarta 1987).

However, this is caused, at least in part, by the marked asymmetry of ab light curves, which does not allow a suitable coverage of the pulsational cycle within the restricted sets of observational data, and the rather small number of objects does not give a strong statistical significance to this ratio.

It is obviously interesting to compare the pulsational behaviour of our sample with the behaviour of variables in the outer regions of the cluster. Moreover, the availability of magnitudes and colours of 'static' structures will allow us to investigate the colour–magnitude (CM) location of the variables. On the first subject, Fig. 5 shows the Bailey diagram (visual amplitude A(V) versus period) for our sample, together with previous data for regularly pulsating variables (no Blazhko effect) from SCB and R96 studies. The remarkably similar distribution of stars in the various samples shows that RR Lyraes in the various cluster regions have a common pulsational behaviour.

The CM diagram of our complete sample of 22 RR_ab and 20 RR_c variables is shown in Fig. 6 together with data for static HB stars from Brocato, Castellani & Ripepi (1995). By excluding V113 and V139 because of their peculiar blue colour, and V105 and V121 because of their peculiar faint magnitude, one derives that the edges of the observed instability strip occur at (B − V) = 0.20 ± 0.02 and 0.45 ± 0.02, and also that the lower envelope of the RR Lyrae distribution can be safely placed at V = 15.14 ± 0.04 mag. Note that we are very confident in the colours of the RR Lyraes near the edges of the instability strip, whereas the few non-variable stars within the instability strip appear in general to be affected by crowding or blending.

3 DISCUSSION AND CONCLUSIONS

In the previous fig. 5, five observational data points are compared with theoretical predictions from pulsating convective models with mass $M = 0.65 M_\odot$, luminosity $\log L/L_\odot = 1.61$ (solid line) and 1.72 (dashed line) and labelled chemical composition. One finds that the left envelope of the RR_ab distribution appears in agreement with the $\log L/L_\odot = 1.61$ line. Taking the pulsational
Figure 5. Bailey amplitude–period diagram for the labelled samples of M5 variables, in comparison with the results of convective pulsating models.

Figure 6. CM diagram of RR Lyrae and HB static stars in M5; data for static stars are from Brocato et al. (1995); solid lines represent the reasonable range for the ZAHB luminosity level.
results at face value, this would suggest a ZAHB luminosity in excellent agreement with theoretical predictions given by Castellani, Chieffi & Pulone (1991) but somewhat lower than the value $\log L/L_\odot = 1.66$ suggested by the more recent ‘improved’ computations of Cassisi et al. (1998, hereafter C98). Note that all the most recent evaluations of such a luminosity, given by various authors under slightly different assumptions, appear to be in the range $1.66 \pm 0.01$ (Caloi, D’Antona & Mazzitelli 1997; Straniero, Chieffi & Limongi 1997).

To discuss such a disagreement, one must realize that while the luminosity of the HB appears as a rather firm theoretical prediction, theoretical pulsator masses rely on the assumption of a solar-like distribution of heavy elements. However, the suggested occurrence of $\alpha$-enhanced mixtures in metal-poor globular cluster stars (see, e.g., Gratton et al. 1997) is not of help, because lower pulsator masses will imply even lower ‘pulsational’ luminosities (see, e.g., fig. 15 in Bono et al. 1997a).

In order to compare theoretical predictions about the boundaries of the instability region with the observational results given in the previous section, one needs an estimate of the cluster distance modulus (DM). Let us assume here the value one would derive from the already quoted C98 evolutionary results, namely $DM = 14.59$ ($\pm 0.04$) mag. On this ground, Fig. 7 compares the CM diagram location of the variables with theoretical predictions evaluated for the purpose of this paper (with the same code and input physics as in Bono et al. 1997b) about the boundaries of the instability strip for $M = 0.65 M_\odot$, $Z = 0.001$ (solar scaled), $Y = 0.24$ and for selected assumptions about the cluster reddening. The theoretical boundaries have been transformed into the observational plane by adopting the Castelli, Gratton & Kurucz (1997a,b) static model atmospheres.

One finds that a good fit of theory to observation would require a negligible amount of reddening, running against a rather well-established reddening of the order of $E(B-V) \sim 0.02$ (see, e.g., R96), if not larger (Gratton et al. 1997). Quite similar results are obtained when R96 data are compared with pulsational predictions in $(V-I)$ colours. Reasonable variations in the distance modulus do not play a relevant role, because of the mild dependence of the blue edge colour on luminosity, nor will the occurrence of $\alpha$-enhanced mixtures again be of help, because lower pulsator masses will imply even cooler blue boundaries (see again Bono et al. 1997a).

However, one finds that a problem arises from the adoption of new model atmospheres by Castelli et al. (1997a,b), because the model atmospheres of Kurucz (1992) adopted in previous works, such as Bono et al. (1997a,b), would give for M5 a ‘pulsational’ reddening of the order of $E(B-V) \sim 0.02$ mag. As it is not clear to us whether ‘new model atmospheres’ means in all cases ‘better models’, and taking also into account reasonable ($\pm 0.02$ mag) errors in the pulsator colours, we conclude that there is a

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**Figure 7.** CM diagram of RR Lyrae stars compared with the theoretical boundaries of the instability, for different assumptions about the cluster reddening.
suggestion (rather than firm evidence) for too-cool FOBE predictions in the adopted theoretical pulsational scenario.

As a conclusion, observational evidence concerning the M5 pulsators appears in marginal disagreement with the observed colour of FOBE, whereas a clearer disagreement appears between the ZAHB luminosities predicted through evolutionary theory and the theoretical Bailey diagram. Before closing the paper, we point out that one should be not too surprised about the quoted disagreements: in all cases we are dealing with rather small quantities $\Delta M_V$ not larger than 0.1 mag, $\Delta(B - V) \sim 0.02$ mag and, in that sense, both evolutionary and pulsational theories appear to be in rather satisfactory agreement with observations. Conversely, when dealing – as we do – with fine details of theoretical predictions, one would be surprised if these results did not show any evidence of the many uncertainties we know exist in the theoretical scenario.

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