DETECTION OF THE EVOLUTIONARY STAGES OF VARIABLES IN M3

J. Jurcsik,1 J. M. Benkő,1 G. Á. Bakos,1,2 B. Szeidl,1 and R. Szabó1

Received 2003 June 25; accepted 2003 September 17; published 2003 October 13

ABSTRACT

The large number of variables in M3 provides a unique opportunity to study an extensive sample of variables with the same apparent distance modulus. Recent, high-accuracy CCD time series of the variables show that according to their mean magnitudes and light-curve shapes, the variables belong to four separate groups. Comparing the properties of these groups (magnitudes and periods) with horizontal-branch evolutionary models, we conclude that these samples can be unambiguously identified with different stages of the horizontal-branch stellar evolution. Stars close to the zero-age horizontal branch show Oosterhoff I (Oo I) type properties, while the brightest stars have Oo II type statistics regarding their mean periods and RRab/RRc number ratios. This finding strengthens the earlier suggestion of Lee, Demarque, & Zinn, connecting the Oo dichotomy to evolutionary effects; however, it is unexpected to find large samples of both of the Oo types within a single cluster, which is, moreover, the prototype of the Oo I class globular clusters. The very slight difference between the Fourier parameters of the stars (at a given period) in the three fainter samples spanning over about 0.15 mag range in $M_V$ points to the limitations of any empirical methods that aim to determine accurate absolute magnitudes of RR Lyrae stars solely from the Fourier parameters of the light curves.

Subject headings: globular clusters: individual (M3) — stars: evolution — stars: horizontal-branch — stars: Population II — stars: variables: other

On-line material: color figures

1. INTRODUCTION

Variable stars in globular clusters are very important objects in understanding horizontal-branch (HB) stellar evolution. They are of the same age, and the spread in their metallicity, if present at all, is supposed to be rather small. Their global properties are well known, but there are still significant uncertainties in tying the basic parameters of the globular clusters (distance, age, and metallicity) to absolute scales. The “second parameter,” which defines the structure of the HB besides metallicity, is still a matter of debate. The systematic differences in the mean periods of RRab stars and in the percentage of the overtone variables (Oosterhoff [Oo] dichotomy) cannot be simply connected to the HB type or the metallicity of the clusters. Lee, Demarque, & Zinn (1990) suggested an evolutionary explanation of the Oo dichotomy and the Sandage period shift, arguing that evolution away from the zero-age horizontal branch (ZAHB) can explain the properties of Oo II clusters. Comparing M2 (Oo II) and M3 (Oo I), Lee & Carney (1999b) draw a similar conclusion, but they also found a 2 Gyr age difference between these clusters. The luminosities of the HB of the different clusters, which are crucial both in the explanation of the Oo dichotomy and the period shift, bear, however, significant uncertainties. Thus, studying stars of different evolutionary stages in a single cluster may have crucial impact on these studies.

M3 is one of the most prominent globular clusters, with a very extensive population of RR Lyrae stars (both of RRab and of RRc) making the cluster an ideal target for the investigation of the HB within the instability strip (IS). The properties of RR Lyrae stars classify M3 as an Oo I type cluster with a larger population of RRab stars than the overtones and with a 0.561 day mean RRab period (Corwin & Carney 2001, hereafter CC01). The $\sim 0.3$ mag range of the mean magnitudes of the RR Lyrae stars is supposed to be real and may be understood in terms of HB evolution. Kaluzny et al. (1998) mentioned that the three brightest RRab stars might already be in an evolved phase of their HB evolution. Clement & Shelton (1999) have drawn attention to the fact that these stars fit the period-amplitude ($P$-$A$) relation of Oo II clusters. This led them also to conclude that the Oo dichotomy is due to evolution and the previously assumed period-amplitude-metallicity relation was just an artifact of different selection effects. On the basis of their magnitudes and positions on the $P$-$A$ plot, CC01 separated a group of RRab stars in M3 being probably already in the late stage of the HB evolution.

In this Letter we present details on the fine structure of the HB of M3 inside the IS that strengthen the results of CC01 and Clement & Shelton (1999). The properties of the variables are explained in the context of the HB stellar evolution.

2. DATA AND RESULTS

Using all the available photometric $V$ observations of M3 variables (CC01; Kaluzny et al. 1998; Carretta et al. 1998; J. Benkő et al. 2003, in preparation, hereafter B03), we constructed complete accurate light curves of $\sim 100$ RRab and $\sim 50$ RRc type stars. As our aim was to study the differences in the light curves’ shapes and the distribution of the mean magnitudes, only stars not affected seriously by any type of modulation (Blazhko, non-radial, and double mode) were used. Constructing the light curves by using all the available measurements can help to eliminate any defect (distortion) that might be present in any of the observations.

A comparison of the light curves from different observations and reduction processes (Jurcsik 2003) showed that the light curves of the inner variables in CC01 have considerably larger scatter and much less reliable mean magnitudes than the B03 data. For the outer variables, the scatter in the $V$ light curves of CC01 is a bit larger than in the B03 and Kaluzny et al. (1998) data. Consequently, we rely on the correctness of the B03 data, and to reach the most accurate light-curve shapes.
we do not simply merge the different data, but if necessary, magnitude offsets of the order of 0.01 mag to the different measurements are added to match the data of the individual variables to the B03 light curves. The error of the intensity mean magnitudes of the variables used in this work is typically less than 0.02 mag in B03; thus this is the typical accuracy of the data that the current study is based on.

The accuracy of the mean magnitudes makes it possible to map the light-curve shapes and periods (Fourier parameters) in the two-dimensional period-magnitude plane. Assuming homogeneous composition, this plane is analogous to the color-magnitude diagram, as variables with the same magnitudes have nearly equal masses within the IS; thus differences in their periods are due only to their different temperatures (colors).

The magnitude distribution of the RR Lyrae stars is shown in the top panels of Figure 1. Both RRab and RRc stars show a relatively wide ~0.3 mag distribution with two central peaks at around 15.67 and 15.63 mag, a flat wide range of brighter stars and a faint tail going down to 15.75 mag. A comparison with HB synthesis results using Dorman (1992) evolutionary models is also shown in Figure 1. Uniform mass and age distributions of the HB stars in the 0.60–0.70 $M_\odot$ and 0–100 Myr intervals are assumed, and the IS of RR Lyrae stars is defined as shown in Figure 4. Synthetic HB results gave $\langle M_{\text{HB}} \rangle = 0.64$ and $\sigma_g = 0.02 M_\odot$, mean mass and mass dispersion values in M3 (Catelan, Ferraro, & Rood 2001). However, as different models have different mass distributions on the HB, if using Dorman (1992) models to synthesize the HB population of M3, other values for $\langle M_{\text{HB}} \rangle$ and $\sigma_g$ may be obtained. Therefore, we tested the synthetic magnitude distribution within the IS using $\langle M_{\text{HB}} \rangle$ and $\sigma_g$ values within the 0.62–0.68 and 0.02–0.03 $M_\odot$ ranges. These simulations led to similar results as for uniform mass distribution, with a bit more narrow density peak when smaller $\langle M_{\text{HB}} \rangle$ and $\sigma_g$ values were assumed. We thus conclude that, taking into account the uncertainties of both the observations and the models, there is a satisfactory agreement between the observed magnitude distribution and synthetic HB results. This global agreement helps in identifying the different magnitude variables with different stages of the HB evolution.

As there is no clear cut between the magnitudes of the different magnitude groups identified in Figure 1, the light-curve shapes help in deciding which group a given star belongs to. In order to check the possible systematic differences between the shapes of the light curves at different mean magnitudes, we compared the progressions of their Fourier parameters as a function of their periods as shown in Figure 2. These plots can be interpreted as changes in the light-curve shapes with decreasing temperature for the four samples that have the same luminosity and composition, and there should be just a very slight (<0.03 $M_\odot$) dispersion in their masses. The most dramatic differences can be seen in the Fourier parameters of the brightest sample, but the other brighter group is also slightly shifted, especially in the higher Fourier components from the fainter stars. The two faint samples seem to follow the same tracks. The larger scatter of the Fourier parameters of the faintest sample may be due to observational inaccuracies, but it cannot be excluded that it reflects intrinsic differences in the light-curve shapes of these stars. The observed main tracks in Figure 2 are very similar to the predicted behavior of the Fourier parameters of constant luminosity, mass, and composition models shown by Dorfi & Feuchtinger (1999). This result strengthens the reality that the three brighter groups represent indeed different luminosity samples.

The period-Fourier amplitude plots shown in Figure 2 are the analogs of the P-A diagram discussed in many papers as a diagnostic tool of the Oo type. CC01 separated a sample of 13 RRab stars in M3, which defined a long period sequence on the P-A diagram. According to their observations, 11 of these stars were brighter than the average magnitude of the RR Lyrae stars. Our measurements confirm this finding; moreover, in our data all these stars belong to the brightest sample, including an additional member of this group, V139.

Figure 3 shows the period distributions in the four different brightness groups and, for comparison, the period distribution

---

**TABLE 1**

**PARAMETERS AND EVOLUTIONARY STAGES IN THE FOUR M3 GROUPS COMPARED WITH DATA OF M2**

| MEAN PERIOD / PERIOD RANGE (DAYS) | $\langle \bar{V} \rangle$ MAGNITUDE $\sigma$ | NUMBER OF STARS | HB EVOLUTIONARY PHASE |
|-----------------------------------|---------------------------------------------|-----------------|------------------------|
| RRab  | RRc | RRab | RRc | RRab | RRc | RRab | RRc | RRab  | RRc | RRab  | RRc | RRab  | RRc | RRab  | RRc |
| 0.685/0.528–0.876 | 0.333/0.273–0.420 | ... | ... | 15.533 | 0.034 | 15.522 | 0.043 | 18 | 12 | M2 |
| 0.670/0.560–0.774 | 0.336/0.251–0.486 | ... | ... | 15.618 | 0.019 | 15.620 | 0.010 | 41 | 9 | Late redward evolution |
| 0.592/0.508–0.673 | 0.323/0.276–0.348 | ... | ... | 15.671 | 0.013 | 15.677 | 0.008 | 22 | 11 | Bluest part of the blue loop |
| 0.551/0.456–0.644 | 0.316/0.284–0.533 | ... | ... | 15.707 | 0.014 | 15.723 | 0.029 | 19 | 8 | Reddest stage and bluward evolution |
| 0.542/0.459–0.643 | 0.319/0.267–0.350 | ... | ... | ... | ... | ... | ... | ... | ... | ZAHB |
Fourier parameters of RR\textit{ab} stars with respect to their pulsation period. The four different magnitude groups follow three different tracks, especially in the higher Fourier components. The most dramatic differences are in the behavior of the brightest sample (triangles), whose amplitudes are significantly larger than the amplitudes of the fainter variables at the same period. The two faintest samples (crosses and filled circles) seem to follow the same sequences; although the larger scatter of the fainter one may be real, larger observational uncertainties as a reason cannot be excluded either. Stars at around $(V) = 15.62$ mag are denoted by open circles. The tracks defined by the fainter samples are very similar to the results of the model calculations of Dorfi & Feuchtinger (1999) for the same mass, composition, and luminosity models at different temperatures. The observed magnitude range of the three fainter samples is about 0.15 mag. The similar behavior of their Fourier parameters indicates serious limitations of any empirical methods that aim to determine the absolute magnitudes of the variables with hundredths of magnitude accuracy exclusively from light-curve parameters. For comparison, RR\textit{ab} stars of M2, a typical Oo II cluster with the same metallicity as M3, are also shown (plus signs). The overlap of the brightest M3 sample with the M2 variables indicates that the brightest stars in M3 share Oo II properties.

The period distributions of RR\textit{ab} stars in the four groups show definite shifts with magnitude. Both the shortest and the longest periods and also the distribution of the periods in the third group are very similar to that of the two fainter groups but are shifted by +0.03 days. The mean period of the brightest stars is 0.12 days longer than in the main group. Jurcsik (1998) explained the Sandage period shift (an increase of the mean period of RR\textit{ab} stars in globular clusters with decreasing metallicity) with the inclination of the RR\textit{ab} IS. The variables in M3 also indicate an inclination of the IS (CC01, their Fig. 9; Bakos & Jurcsik 2000). The increased luminosities of the two brighter samples account for $\sim 0.025$ and $\sim 0.07$ day longer periods, respectively, according to the linear pulsation equation. To explain the observed 0.05 and 0.12 day longer periods in these samples, cooler temperatures and/or smaller masses of these stars have to be also assumed.

The period distribution of the faintest stars is the same as that of the most populous group. For the smaller sample of the RR\textit{c} stars, a similar investigation of their period distribution is not possible; however, it is noteworthy that the six longest period RR\textit{c} stars belong to the brightest group.

### 3. CONCLUSIONS

On the basis of the comparison of our data with HB evolutionary models, the four groups at different mean brightness can be identified with different stages of the HB stellar evolution as shown in Figures 1 and 4. Table 1 summarizes the observed properties and the suggested evolutionary stages of the variables belonging to the four groups. The faintest sample (27) can be identified with variables close to their ZAHB positions. Most of the stars in our sample (50) are evolving blueward on the HB. Stars belonging to the 0.05 mag brighter sample (33) are at the hottest part of the blue loops, while the brightest stars (32) are in the late redward phase of their HB evolution. It is interesting to note that among the overtone variables, most of the stars belong to this group, which indicates that in M3, on the average, RR\textit{c} stars are already in a later phase of their HB evolution than the RR\textit{ab} variables.

If we compare the mean periods of RR\textit{ab} stars and the percentage of the RR\textit{c} variables of the ZAHB and the blueward evolving stars with that of the brightest most evolved sample (0.55 and 0.67 days; 22% and 56%, respectively), an Oo I and an Oo II population emerge. The Fourier parameters of RR\textit{ab} stars in M2, a globular cluster with the same metallicity as M3 but with Oo II properties, are also shown in Figure 2 using Lee & Carney (1999a) data. The 11 M2 variables and the 14 brightest RR\textit{ab} stars in M3 cover similar range in period and define the same sequences (V10 in M2 with 0.87 day period is not shown in Fig. 2). The large scatter of these tracks is most probably intrinsic and is due to the larger range in the
the brightest M3 sample is V70, an anomalously long-period RR because of the smaller sample sizes. The variable with 0.486 day period in the RR stars do not show any significant differences; however, it may be because of the smaller sample sizes. The variable with 0.486 day period in the brightest M3 sample is V70, an anomalously long-period RRc star. The top panel shows the period distribution in M2. Although the RRab periods in M2 are even a bit longer than in the brightest group of M3, both the larger percentage of RRc stars and the longer periods of RRab stars of the brightest sample resemble the similar properties of the Oo II M2 variables. [See the electronic edition of the Journal for a color version of this figure.]

evolutionary status of the most evolved HB stars. The period distribution in M2, as shown in Figure 3, is also similar to that of the brightest M3 sample in accordance with our conclusion that the brightest stars have Oo II characteristics. This is the first direct evidence of the Oo dichotomy in a single cluster with homogeneous metallicity.

The fact that the Oo dichotomy in M3 can be consistently explained by evolutionary effects is a strong constraint for its interpretation and favors the hysteresis hypothesis originally proposed by van Albada & Baker (1971). The hysteresis, namely, that mode switching from overtone to fundamental takes place at a lower temperature than in the opposite direction, may account for both the larger percentage of the overtones and the longer period of the fundamentals during the late redward phase of the HB. A similar conclusion has already been drawn by Clement & Shelton (1999) from the comparison of the $P$-$A$ diagrams of different metallicity clusters and from the existence of three bright and large-amplitude RRab stars in M3. Lee et al. (1990) and Lee & Carney (1999b) explained the Oo dichotomy and the period shift by HB stellar evolution, but their interpretation was drawn from the comparison of the properties of different clusters with order of gigayear age differences, while the age difference between the Oo I and Oo II populations in M3 is smaller than 100 Myr.

As a summary, we succeeded in discriminating the different stages of HB stellar evolution using accurate light curves and mean magnitudes of the variables in M3. A comparison with HB evolutionary models does not reveal any significant discrepancy between observations and model predictions. This result helps in studying the “fine structure” of the HB and can be the base of a more precise distance estimate of RR Lyrae variables. However, the similarity of the light curves (Fourier parameters) of variables in a $\sim 0.15$ mag range imposes strong limits on the accuracy of any empirical method (e.g., Kovács & Walker 2001), which derives the magnitudes of the stars solely from the Fourier parameters of their light curves.

This work has been supported by OTKA grant T43504 and T38437. We would like to thank the stimulating criticism of the anonymous referee that helped to improve the content of the Letter significantly.

REFERENCES

Bakos, G. Á., & Jurcsik, J. 2000, in ASP Conf. Ser. 203, The Impact of Large-Scale Surveys on Pulsating Star Research, ed. L. Szabados & D. Kurtz (San Francisco: ASP), 255
Carretta, E., Cacciari, C., Ferraro, F. R., Fusi Pecci, F., & Tessicini, G. 1998, MNRAS, 298, 1005
Catelan, M., Ferraro, F. R., & Rood, R. T. 2001, ApJ, 560, 970
Clement, C., & Shelton, I. 1999, ApJ, 515, L85
Corwin, T. M., & Carney, B. W. 2001, AJ, 122, 3183 (CC01)
Dorf, E. A., & Feuchtlinger, M. 1999, A&A, 348, 815
Dorman, B. 1992, ApJS, 81, 221
Harris, W. E. 1996, AJ, 112, 1487
Jurcsik, J. 1998, A&A, 333, 571
———. 2003, in IAU Colloq. 193, Variable Stars in the Local Group, ed. D. Kurtz & K. Pollard (San Francisco: ASP), in press
Kaluzny, J., Hilditch, R. W., Clement, C., & Rucinski, S. M. 1998, MNRRAS, 296, 347
Kovács, G., & Walker, A. 2001, A&A, 371, 579
Lee, Y.-W., & Carney, B. W. 1999a, AJ, 117, 2868
———. 1999b, AJ, 118, 1373
Lee, Y.-W., Demarque, P., & Zinn, R. 1990, ApJ, 350, 155
van Albada, A. R., & Baker 1971, ApJ, 169, 311