Evolution of Horizontal Branch Stars in Globular Clusters: The Interesting Case of V79 in M3

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ABSTRACT

New observations of variable stars in the globular cluster M3 reveal that the RR Lyrae variable V79 is a double-mode (RRd) variable with the first overtone mode dominating. In all previous studies, V79 was found to be a fundamental mode (RRab) pulsator with an irregular light curve. This is the first observed mode switch for an RR Lyrae variable and it is direct observational evidence for blueward evolution of horizontal branch stars in the Oosterhoff type I cluster M3. It also demonstrates that there is a connection between the Blazhko effect and pulsational mode mixing in RR Lyrae variables. These new observations also show that the strength of the overtone oscillations in the RRd star V68 in M3 may have increased in the last 70 years, thus indicating blueward evolution for V68 as well.

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A survey of previously published investigations of RRd stars in Oosterhoff type II systems indicates that there is marginal evidence for an increase in the strength of fundamental mode oscillations in two stars: V30 in M15 and AQ Leo. If these increases are confirmed by future observations, it will indicate redward evolution for RRd stars in type II systems.

Subject headings: globular clusters: individual: (M3,M15) — stars: evolution — stars: horizontal-branch — stars: variables: RR Lyrae

1. Introduction

A standard method for investigating the evolution of horizontal branch stars is to analyze the period changes of RR Lyrae variables in globular clusters. Period increases should indicate redward evolution, while decreases indicate blueward evolution, and the rates of change give information about the time scales. The models of Sweigert & Renzini (1979) and Lee et al. (1990) predict that the RR Lyrae variables in the Oosterhoff type I clusters cross the instability strip during their ZAHB phase and are therefore expected to have period decreases, which are followed later by increases, when the stars evolve away from the ZAHB. For the RR Lyrae variables in the more metal-poor Oosterhoff type II clusters, the models predict only increasing periods, because these stars cross the instability strip after their ZAHB phase. Since there are a few globular clusters that have been observed over an interval of 100 years, it should be possible to use these observations to test the models. Unfortunately, the observational data do not give definitive results (cf. Smith 1995, Rathbun & Smith 1997). The evolutionary period changes seem to be masked by a period change noise of irregular character. Sweigert & Renzini (1979) have demonstrated that this noise could be caused by mixing events that alter the hydrostatic structure of the core and thus affect the star’s pulsation period. Because of this, the observed rates of change are sometimes an order of magnitude too large and of the wrong sign, when compared with the rates predicted by evolutionary theory. However, if one assumes that, for a particular cluster, the mean rate of period change is a measure of the evolutionary change, then it may be possible to compare the observations with theory. Lee (1991) took this approach and found that the observed period changes of the RR Lyrae stars in five well observed clusters could be attributed to evolutionary effects, provided the noise is random and of the order of 0.07 days per million years.

Another way to study the evolution of HB stars is to examine the distribution of periods and modes of pulsation of RR Lyrae variables in globular clusters of the two Oosterhoff
types. Some years ago, van Albada & Baker (1973) postulated that the difference in the period distributions for the Oosterhoff type I and II clusters is due in part to hysteresis in pulsation. According to their theory, the RRab variables in the type I clusters enter the instability strip as fundamental mode pulsators (RRab stars) and evolve from red to blue, while the stars in type II clusters enter as first overtone pulsators (RRc stars) and evolve from blue to red. Because of hysteresis, the transition period at which a star switches between the fundamental and first overtone modes will be different for the two cluster types, and consequently, the mean periods of both the RRc and RRab stars will be affected as well. The RR Lyrae variables in type II clusters should switch modes at longer periods and as a result, their mean periods will be longer than those in the type I clusters. Also, the Oosterhoff type II clusters should have a higher proportion of RRc stars. These are the observed characteristics of the two Oosterhoff groups. If the van Albada & Baker scenario is correct, then the transition between the $ab$– and $c$–type RR Lyrae variables should occur near the blue edge for fundamental mode pulsation in Oosterhoff type I clusters and near the red edge for the first overtone in Oosterhoff type II clusters. Using up-to-date convective pulsation models to locate the instability strip on the HR diagram, Bono et al. (1994) and Cox (1995) have presented evidence to indicate that this is, in fact, the case.

In the present investigation, we suggest another method for studying HB evolution: monitoring long term changes in the pulsation characteristics of double-mode RR Lyrae (RRd) stars. If an RRd star is evolving blueward, then over a period of time, the amplitude of the first overtone should gain in strength relative to fundamental, but if it evolves redward, the strength of fundamental mode oscillations should increase. Our study is motivated by the recent discovery of Kaluzny et al. (1997, hereafter KHCR) that V79 in M3, previously classified as RRab, is now an RRd star with the first overtone mode dominating. The KHCR finding was based on observations made in 1996.

2. Analysis of V68 and V79 in M3

The 1996 observations of M3 were obtained on nine nights in the interval March 19 to April 2 by one of us (RWH) with the 1 meter Jacobus Kapteyn telescope at the Observatorio del Roque de Los Muchachos, La Palma. The observations, which include $V$ photometry for 42 RR Lyrae variables on 176 frames, and the reduction procedures, have been discussed by KHCR. One of the two previously known RRd variables, V68, was among the 42 stars and so we have included it in our investigation. (V87, the other RRd star was not in our field of view.) A finding chart for the variables in M3 was published by Bailey (1913). We determined the primary periods for V68 and V79 with a computer program that
utilized Stellingwerf’s (1978) phase dispersion minimization (PDM) technique with a (5,2) bin structure. To search for the secondary period, we derived a mean light curve by fitting a cubic spline interpolating function to the bin means, then measured the residuals from this curve and applied the PDM technique to the residuals. Next, we corrected the magnitudes by subtracting the mean curve for the secondary period from the raw magnitudes and then, again applied the PDM technique to obtain a final value for the primary period. Light curves for V68 and V79 are shown in Figures 1 and 2. The top panel of each figure shows the ‘raw’ magnitudes plotted with the primary period, the first overtone. The curves in the middle and bottom panels show respectively, the corrected magnitudes plotted with the first overtone period and the residuals plotted with the secondary (fundamental) period, both with the interaction frequencies \((1/P_1 \pm 1/P_0)\) also removed.

To assess the long term behavior of these stars, we compared our results with those of an earlier study of the RRd stars in M3 by Nemec & Clement (1989, hereafter NC). The NC study was based mainly on data from a combination of three sets of observations made in the interval 1920 to 1926 and published by Larink (1922), Muller (1933) and Greenstein (1935). NC found that V68 was an RRd star with the fundamental mode dominant, but they considered V79 to be an RRab star. The light curve of V79 (see Figure 2 of NC) showed night-to-night scatter, but a PDM period search of the residuals did not reveal any periodicity in the range expected for first overtone oscillations (see Figure 3 of NC). They estimated that if there were any first overtone oscillations, they would have an amplitude less than 0.25 mag.

We summarize the pulsation characteristics of V68 and V79 in Table 1. In columns 2 and 3, we list their co-ordinates in arcseconds relative to the cluster center according to Sawyer Hogg’s (1973) catalogue, in columns 4 to 8, we list the first overtone and fundamental periods \((P_1\) and \(P_0)\), their corresponding amplitudes \((A_1\) and \(A_0)\) and amplitude ratios derived from the 1996 observations and in the final column, we list the amplitude ratios for 1920–1926 based on NC’s study. The data of Table 1 illustrate that for both stars, the first overtone oscillations have grown in strength since the 1920s, but for V79, the change is more striking.

In order to find out what happened to V79 in the intervening years, we used the PDM technique to analyze other published observations that were suitable for period searches. These included observations obtained in the intervals 1938 to 1962 (Szeidl 1965) and 1946 to 1948 (Belserene 1952). In the PDM technique, a \(\Theta\) statistic which is a measure of the scatter on the light curve is evaluated for a series of periods and the period for which \(\Theta\) is a minimum is considered to be the best period. In Figure 3 we show plots of \(\Theta\) versus period for the raw data over the range \(0^d34\) to \(0^d50\), for the four epochs. The plot for the 1996
data in the bottom panel of the figure indicates that the best period is 0\textsuperscript{d}.358. However, the plots for the first three epochs all show a clear minimum at a period of approximately 0\textsuperscript{d}.4833 and period searches of the residuals measured from their corresponding primary light curves did not reveal any oscillations in the overtone mode even though there were variations in the amplitude. Our analysis also indicates that the fundamental period of V79 has decreased by a substantial amount in the last 35 years. The 0.4833 day period derived from the previous studies is significantly longer than the fundamental period \(P_0 = 0\textsuperscript{d}.480\) that we determined for the 1996 observations and listed in Table 1. If we plot the 1996 data with the longer period, it introduces a phase shift that increases the scatter on the light curve in the bottom panel of Figure 2. We therefore conclude that two things have happened to V79 between 1962 and 1996. First overtone oscillations have either commenced or increased significantly and there has been an abrupt decrease in the fundamental period.

In his study of period changes of the RR Lyrae variables in M3, Szeidl (1965) found that the O–C diagram for V79 had a discontinuity between 1926 and 1938 and consequently, he was unable to detect any systematic period change for the star. Rathbun & Smith (1997) cited V79 as an example of a star that has “period changes so erratic as to be impossible to even approximately describe with a single number.” If the large abrupt decrease we have detected in \(P_0\) the fundamental period of V79 was caused by evolution on the horizontal branch, then an O–C diagram is not a useful tool for studying evolutionary period changes of RR Lyrae variables, at least not for stars like V79 in M3.

Since, prior to 1962, V79 was an RRab star with an irregular light curve: a ‘Blazhko’ variable, our investigation provides some insight into the actual cause of the Blazhko effect in RR Lyrae variables. According to Smith (1995), most speculation has centered on two possibilities: (1) that the effect is a “consequence of some type of mixing of pulsational modes” and (2) that the effect is “related to magnetic cycles in the stars, perhaps coupled with rotation”. Since we now know that at least one ‘Blazhko’ variable, V79 in M3, has exhibited mixed mode pulsations, we consider the first possibility to be more feasible.

It appears that regular monitoring of stars like V79 in M3 can provide important information about stellar evolution. If there are any available unpublished observations of this star between 1962 and 1996, it would be very informative to analyze them. It would be particularly interesting to know if there has been any change in luminosity or color because this may put constraints on the boundaries of the different pulsational modes in the HR diagram. We should also point out that there are other interesting stars in M3 that merit further investigation. For example, NC noted that the RRab star V28 was a promising RRd candidate. Unfortunately, it was not in the field of view for our present study. Perhaps V28 has also started to switch modes or will do so in the near future. It would be interesting to find out.
3. Evidence for evolution in other RRd stars

We have presented evidence that indicates that two RRd stars in M3 are evolving blueward. Are the RRd stars in Oosterhoff type II systems evolving redward? This question was addressed by Purdue et al. (1995) in a study of the long term behavior of RRd stars in the Oosterhoff type II cluster M15. They noted that the fundamental mode oscillations in V30 increased in strength relative to the first overtone between 1941 and 1991. In fact, their analysis suggests that the change happened rather abruptly in the 1950s. A similar situation occurs for the field RRd star, AQ Leo, which has periods and a period ratio similar to those of RRd stars in Oosterhoff type II systems. Jerzykiewicz et al. (1982) compared the amplitude differences between a series of observations made in 1960-1961 and another in 1973-1974 and found that the first overtone amplitude decreased by an amount 0.012 ± 0.011 while the fundamental mode amplitude increased by 0.017 ± 0.011. They also found that an abrupt increase in the first overtone period occurred in the early 1970s. They stated that their findings did not give direct evidence for mode switching, but that it is a possibility. The increase in strength of the fundamental mode oscillations and the period increase are events that are expected to occur if the star is evolving redward.

Our investigation has shown that high quality photometry of RR Lyrae stars, particularly RRd stars and stars that exhibit the Blazhko effect can provide useful information about the evolution of horizontal branch stars. We expect that future studies will confirm this.

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Table 1: Derived properties for the RRd stars in M3

<table>
<thead>
<tr>
<th>Star</th>
<th>$x''$</th>
<th>$y''$</th>
<th>$P_1$</th>
<th>$P_0$</th>
<th>$A_1$</th>
<th>$A_0$</th>
<th>$A_1/A_0$</th>
<th>$A_1/A_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>V68</td>
<td>+21.9</td>
<td>+174.8</td>
<td>0.356</td>
<td>0.479</td>
<td>0.389</td>
<td>0.348</td>
<td>1.12 ± 0.10</td>
<td>0.72 ± 0.20</td>
</tr>
<tr>
<td>V79</td>
<td>+43.4</td>
<td>+349.4</td>
<td>0.358</td>
<td>0.480</td>
<td>0.337</td>
<td>0.195</td>
<td>1.73 ± 0.13</td>
<td>&lt; 0.2</td>
</tr>
</tbody>
</table>

Fig. 1.— Light curves for V68 based on the 1996 observations. In the upper panel, the raw magnitudes have been plotted with the dominant period, the first overtone. In the middle panel, the corrected (prewhitened) magnitudes have been plotted with the overtone period and in the lower panel, the (prewhitened) residuals have been plotted with the fundamental period. The different symbols denote observations made on different nights. The large night-to-night scatter of the points in the upper panel is typical for a double-mode pulsator. The spread of the points on curves in the lower panels is much less pronounced because after prewhitening, the scatter is reduced.
Fig. 2.— Light curves for V79 based on the 1996 observations. The arrangement of the curves is the same as in Fig. 1.
Fig. 3.— The Θ transforms (plots of Stellingwerf's Θ statistic versus period) for V79, for four different epochs. The period for which Θ is a minimum is considered to be the best period. The diagram illustrates that for observations prior to 1962, the best period was approximately $0^4.48$, but in 1996, it was $0^4.36$. This indicates a mode switch from the fundamental to the first overtone.