THE RR LYRAE PERIOD-AMPLITUDE RELATION AS A CLUE TO THE ORIGIN OF THE OOSTERHOFF DICHOTOMY

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ABSTRACT

An examination of the period—V amplitude relation for RRab stars (fundamental mode pulsators) with “normal” light curves in the Oosterhoff type I clusters M3 and M107 and in the Oosterhoff type II clusters M9 and M68 reveals that the V amplitude for a given period is not a function of metal abundance. Rather, it is a function of the Oosterhoff type. This result is confirmed by published observations of RRab stars in M4, M5, and M92. A method devised by Jurcsik & Kovács has been used to determine whether the light curve of an RRab star is “normal” or “peculiar.” Although M3 is considered to belong to the Oosterhoff type I group, it has three bright RRab stars that seem to fit the period-amplitude relation for Oosterhoff type II RRab stars. There is evidence that these bright stars are in a more advanced evolutionary state than the other RRab stars in M3, thus leading to the conclusion that the Oosterhoff dichotomy is due to evolution. Our result gives support to the Lee, Demarque, & Zinn hypothesis that most RR Lyrae variables in Oosterhoff type I clusters are zero-age horizontal branch (ZAHB) objects, while those in the Oosterhoff type II clusters are more evolved. This may have important implications for the derived ages of Oosterhoff type II clusters. If their RR Lyrae variables have all evolved away from the ZAHB, then their ages have been overestimated in studies that assume they are ZAHB objects.

Subject headings: globular clusters: individual (M3, M4, M5, M9, M68, M92, M107)—stars: fundamental parameters—stars: horizontal-branch—stars: variables: other (RR Lyrae)

1. INTRODUCTION

It has often been assumed that the period-amplitude relation for fundamental mode RR Lyrae (RRab) stars is a function of metal abundance. Forty years ago, in a study of the period-$V_{\text{mag}}$ amplitude diagram for approximately 50 field RRab stars, Preston (1959) demonstrated that the more metal-poor and more metal-rich stars appeared to define two sequences well separated in amplitude. Subsequently, Dickens & Saunders (1965) and Dickens (1970) found similar results for RRab stars in globular clusters. Then, in a study of six well-observed clusters, Sandage (1981b, hereafter S81b) quantified this result. He measured a period shift $\Delta \log P$ for each cluster relative to the mean period-amplitude relation for M3 and found a correlation between $\Delta \log P$ and metal abundance in the sense that the more metal-poor RR Lyrae variables had longer periods. As a result of this, some investigators have used the period-amplitude relation as an indicator of metal abundance, particularly in faint systems in which it is difficult to estimate it by other methods. Sandage’s (S81b) result was based mainly on photographic data, but in the last 10 years, CCD detectors have been widely used for observations of RR Lyrae variables in globular clusters. CCDs are linear detectors, and this makes the photometry more accurate. They also have a higher quantum efficiency than photographic emulsions so that exposure times can be shorter. As a result, the time and magnitude at maximum and minimum light can be more precisely established and it is possible to derive more accurate amplitudes. Another problem with earlier studies was that, in some cases, stars with nonrepeating light curves—stars that exhibit the Blazhko effect—were included in the samples. The amplitude of light variation for Blazhko stars varies over timescales longer than the basic pulsation period. Thus, if Blazhko variables are not identified, they introduce scatter into the period-amplitude (P-A) diagram. To address this problem, Jurcsik & Kovács (1996, hereafter JK) recently devised a compatibility test for identifying Blazhko variables.

The purpose of our investigation is to use $V$ amplitudes derived from CCD photometry to reexamine the P-A relation for RR Lyrae variables in globular clusters of both Oosterhoff types and to apply JK’s test so that Blazhko variables can be identified. In Table 1, we list [Fe/H], horizontal branch classification, and Oosterhoff (1939, 1944) type for seven clusters for which published $V$ photometry is available. The [Fe/H] is on the system of Jurcsik (1995), and the horizontal branch (HB) classification is indicated by the quantity $(B-R)/(B+V+R)$ defined by Lee, Demarque, & Zinn (1994). A negative value for this quantity indicates that most of the HB stars are on the red side of the instability strip, and a high positive value indicates that most are on the blue side.

2. THE COMPATIBILITY TEST OF JURCSIK & KOVÁCS

The modus operandi of JK was to characterize the light curve systematics of a sample of 74 RRab stars with normal light curves by studying the interrelations among the Fourier parameters. Specifically, they derived a set of nine equations for calculating the Fourier amplitudes $A_1$ to $A_5$ and the phase differences $\phi_0$ to $\phi_1$. If, for a particular star, the calculated value for any one of the parameters is not in good agreement with the observed value, the star’s light curve is considered to be peculiar. They illustrated the effectiveness of their method with a study of RV UMa, an RR Lyrae star that exhibits the Blazhko effect. An independent demonstration of the validity of JK’s test comes from a study of V12 in NGC 6171 (M107) by Clement & Shelton (1997, hereafter CS97). CS97 observed...
this star in two different years, and the light curve appears to repeat well from cycle to cycle. Nevertheless, the JK compatibility test indicates that the light curve of V12 is peculiar. It turns out that this is indeed the case if one compares the light curve of CS97 with an earlier one published by Dickens (1970). Both the shape and amplitude of the curve of V12 changed dramatically between the two epochs.

3. THE PERIOD-AMPLITUDE RELATION OF RR LYRAE VARIABLES

3.1. The Oosterhoff Type I Clusters M3 and M107

In the top and middle panels of Figure 1, we show the period–V amplitude relations for the Oosterhoff type I (OoI) globular clusters, M3 and M107. The data for M3 are from Kaluzny et al. (1998), and the data for M107 are from CS97. To establish which RRab stars in M3 and M107 had peculiar light curves, we applied JK’s compatibility test using equations recently derived by Kovács & Kanbur (1998) from a sample of 257 RRab stars. What we see in the top and middle panels of the figure is that most of the RRab stars with peculiar light curves (open circles) have lower amplitudes than other stars with the same period. According to Szegedi (1988) and JK, the maximum amplitude of a Blazhko variable fits the period-amplitude relation for regular RRab stars. Thus, these stars are probably Blazhko variables that were not observed at a time when the amplitude was at its maximum. In the M3 plot, the squares represent three regular RRab stars (V14, V65, and V104) that are brighter than the other stars. Kaluzny et al. (1998) concluded that these three stars are probably in a more advanced evolutionary state than the others. In the bottom panel of Figure 1, we plot the RRab stars: V29 in M4 and V8 and V28 in M5. These are stars that JK classified as normal and for which published V photometry is available. Clementini et al. (1994) observed M4, and Storm, Carney, & Beck (1991) observed M5. Also plotted are the V amplitudes that CS97 derived from Reid’s (1996) observations of RRc stars in M5.

The straight line shown in each panel is a least-squares fit to the principal sequence of regular RRab stars in M3 (filled circles). We can readily see that the regular RRab stars in the three OoI clusters (M107, M4, and M5) fit the P–A relation for M3. There is no evidence for a shift in log P, even though all three of these clusters are more metal rich than M3. The situation may be different, however, for the RRc stars. The curve to the left of log P = −0.4 in each panel of the diagram is a fit to the RRc stars in M3, and in this case, the P–A relations for M5 and M107 are shifted to shorter periods than M3.

3.2. The Oosterhoff Type II Clusters M9 and M68

In the top panel of Figure 2, we plot the P–A, diagram for M9, based on data published by Clement & Shelton (1999). The solid line is a least-squares fit to RRab stars in M9, and the dashed line is the fit to M3 shown in Figure 1. The two curves are the fits to the RRc stars in M3 and M9. M3 is among the most metal poor of the OoII clusters and M9 is among the most metal rich of the OoII clusters, but the diagram shows that there is a definite period shift between the two for both RRab and RRc stars. This is the Oosterhoff dichotomy. In the middle panel of Figure 2, the M68 data of Walker (1994) are plotted. JK found that two RRab stars in M68 (V23 and V35) had normal curves, and so these are plotted as filled circles. The remaining RRab stars are plotted as open circles. The M68 RRab stars with peculiar light curves generally have lower amplitudes than those with normal curves, like M3 and M107 in Figure 1. However, this trend is not apparent in M9. Perhaps this is because the stars with irregular light curves are observed at maximum amplitude. In the bottom panel of Figure 2, we plot amplitudes derived from the observations of Carney et al. (1992) for two M92 RRab stars classified as regular by JK. Also included in the bottom panel are the three bright stars in M3. All of the regular RRab stars plotted in Figure 2 seem to

### Table 1: Clusters Metal Abundances and HB Type

| Cluster | [Fe/H] | \((B-R)/(B+V+R)\) | Oosterhoff Type |
|---------|--------|----------------|---------------|
| M107    | −0.68  | −0.76          | I             |
| M4      | −1.11  | −0.07          | I             |
| M5      | −1.25  | 0.19           | I             |
| M3      | −1.47  | 0.08           | I             |
| M9      | −1.72  | 0.87           | II            |
| M68     | −2.03  | 0.44           | II            |
| M92     | −2.31  | 0.88           | II            |

*From Jurcsik 1995.
† From Lee et al. 1994.
### Table 2

| Star      | Period (days) | ΔlogP | (V)  | ΔV  |
|-----------|---------------|-------|------|-----|
| V14 ...... | 0.6359019     | 0.044 | 15.57| 0.13|
| V65 ...... | 0.6683397     | 0.078 | 15.53| 0.15|
| V104 ..... | 0.5699231     | 0.059 | 15.60| 0.10|

#### 3.3. The Unique Case of M3

For OoI clusters like M3, the models of Lee et al. (1990) predict that RR Lyrae stars evolve blueward across the instability strip on the ZAHB, but when they evolve away from the ZAHB, they become brighter and redder. Clement et al. (1997) found evidence for blueward evolution of the M3 star V79 because of a mode switch. Before 1962, V79 was an RRab star with a period of 0.483 days, but in 1996, it was an RRcd star with the first overtone mode dominant. This mode switch has since been confirmed by Corwin, Carney, & Allen (1999) and Clement & Goranskij (1999), who found that it occurred in 1992. The mean V magnitude of V79 is 15.71 comparable to the mean magnitude (15.69) of the 21 RRab stars that fit the P-A relation for Ooi clusters (filled circles, Fig. 1), presumably all ZAHB stars. However, the three stars V14, V65, and V104 are brighter. Consequently, Kaluzny et al. (1998) concluded that they are in a more advanced evolutionary state. In addition, these three bright stars fit better to the P-A relation for the OoII RRab stars and their mean period is 0.625 days, which is an appropriate value for an OoII cluster. In Table 2, we list their periods, period shifts (ΔlogP), mean V magnitudes, and ΔV relative to other RRab stars with the same amplitude (i.e., the ones that fit on the straight line of Fig. 1). The above discussion indicates that there are RR Lyrae variables with characteristics of the two Oosterhoff groups in this one cluster. Assuming there is no variation in metal abundance among the stars of M3, this is further evidence that the P-A relation for RRab stars is not a function of metal abundance.

If the P-A relation is not correlated with metal abundance, then why was such a correlation found by previous investigators? One reason is that OoI clusters are, in general, more metal poor than OoII clusters. As a consequence of this, a difference in the P-A relation for clusters of the different Oosterhoff groups could be attributed to a difference in metal abundance. However, Sandage’s analysis indicated that the ΔlogP–metal abundance correlation exists among clusters of one Oosterhoff type. This is documented in column (11) of Table 7 in S81b. The P-A relations for the OoI clusters M4 and NGC 6171 (M107) are shifted to short periods compared with M3. We believe that this apparent correlation probably occurs because of a selection effect in the choice of the M3 sample. The M3 data were taken from the study of Roberts & Sandage (1955), whose objective was to determine reliable colors for RR Lyrae variables, and so they excluded stars with nonrepeating light curves. As a result, stars like those plotted as open circles in our P-A relation for M3 were not included in their study. This makes the P-A relation for M3 appear to be shifted to longer periods than the other OoI clusters. In addition, the fact that some of the M3 RR Lyrae variables have OoII characteristics must also be a contributing factor. (It must also be acknowledged that in clusters like M4 and M107, the period at which the transition between fundamental and overtone mode pulsation occurs is shorter than in M3. However, the short-period fundamental mode pulsators in these clusters have nonrepeating light curves.)

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**Fig. 2.** Period-amplitude relation for the Oosterhoff type II clusters. **Top and middle:** Symbols are triangles for the RRc stars, filled circles for regular RRab stars, and open circles for the ones with peculiar light curves. **Bottom:** Circles represent two regular RRab stars in the OoII cluster M92, and the three squares are the three evolved stars in the OoI cluster M3. In each panel, the solid straight line is a least-squares fit to RRab stars in M9, and the dashed line is the fit to M3 shown in Fig. 1. The two curves are the fits to the RRc stars in M3 and M9. The curve and line for M9 are both displaced to longer periods than those for M3, demonstrating that the RR Lyrae variables in OoI clusters have longer periods than those in the OoII clusters. The diagram shows that metal abundance does not affect the P-A relation for “regular” RRab stars in these three OoII clusters and that the three bright stars in M3 lie close to the OoII P-A relation.
M3 is not the only cluster that has RR Lyrae variables with the characteristics of both Oosterhoff groups; ω Centauri is another. In a study of ω Cen, Butler, Dickens, & Epps (1978) commented that although it is generally assumed to be an OoII cluster, some of its RR Lyrae variables have OoI characteristics. This can account for the S81b finding that its P-A relation is shifted to shorter periods than that of M15 and to longer periods than M3.

3.4. The Period-Luminosity-Amplitude Relation

Sandage (1981a) showed that there is a period-luminosity-amplitude (P-L-A) relation for RRab stars in the sense that, for a given amplitude (or brightness), stars have longer periods. He demonstrated this with photographic observations of two clusters, M3 (Robert & Sandage 1955) and ω Cen (Butler et al. 1978). His approach was to calculate the mean apparent bolometric magnitude for the RR Lyrae variables in a particular cluster and then use van Albada & Baker’s (1971) equation relating pulsation period, mass, temperature, and absolute bolometric magnitude to derive a “reduced” period for each star. This is the period the star would have if its $m_{bol}$ had the same value as the cluster mean. A plot of amplitude against reduced period shows much less scatter than a regular period-amplitude plot, and if the masses of the RR Lyrae stars in a particular cluster are the same, this implies that the amplitude is a function of temperature. S81b’s correlation between $\Delta \log P$ and metal abundance was derived from P-A relations plotted with reduced periods. Nevertheless, the plot for NGC 6171 shows considerable scatter. We believe that this can be attributed to the fact that Blazhko variables were included in his sample. The P-L-A relation does not apply to Blazhko variables.

It is significant that Sandage showed that the P-L-A relation holds for both ω Cen and M3 because these two clusters have stars with properties of both Oosterhoff groups. Even though the P-A relation for RRab stars is a function of Oosterhoff type, a P-L-A relation seems to be valid for stars in a cluster that belongs to both groups. If there is a unique period-amplitude relation for RRab stars on the ZAHB, then the P-L-A relation can be used to estimate the apparent magnitude of the ZAHB in any cluster, regardless of its Oosterhoff type, as long as it has RRab stars with normal light curves. However, an examination of the data in Table 2 indicates that the period shift (at constant amplitude) for the three bright stars in M3 can not be completely accounted for by a difference in luminosity. According to van Albada & Baker’s (1971) pulsation equation, $\Delta \log P/\Delta m_{bol}$ is 0.34 for constant mass and temperature, but the mean $\Delta \log P/\Delta V$ derived for the three bright stars in M3 is 0.48 with $\sigma = 0.10$. Thus, there must be a difference in mass and/or temperature as well.

4. ImPLICATIONs FOR AGES OF GLOBULAR ClUSTERS

In recent years, there has been considerable discussion in the literature (e.g., Chaboyer, Demarque, & Sarajedini 1996; Stetson, Vandenberg, & Bolte 1996) about the range of ages of Galactic globular clusters and also about the question of whether or not metal-poor clusters are older than metal-rich clusters. These issues have not yet been resolved, but our results may have some impact on this problem. In some investigations, e.g., Gratton (1985), the cluster age is derived from the difference between the ZAHB and the main-sequence turnoff ($\Delta V_{ZAHB}$). In these cases, the faintest stars on the HB in the vicinity of the RR Lyrae instability strip are assumed to be ZAHB objects, but if they are in fact at a more advanced evolutionary state, the apparent luminosity of the ZAHB is overestimated. As a result, $\Delta V_{ZAHB}$ is also overestimated, and this leads to overestimation of the cluster age. This could cause an apparent age-metallicity relation.

It will be very interesting to see if other studies of RR Lyrae variables confirm our conclusion that the period-amplitude relation for fundamental mode pulsators depends on evolutionary state and not on metal abundance.

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