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METAL ABUNDANCES OF RR LYRAE STARS IN THE METAL-RICH GLOBULAR CLUSTER NGC 6441[1]

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ABSTRACT

Low-resolution spectra have been used to measure individual metal abundances of RR Lyrae stars in NGC 6441, a Galactic globular cluster known to have very unusual horizontal-branch morphology and periods of the RR Lyrae stars for its high metallicity. We find an average metal abundance of [Fe/H] $= -0.69 \pm 0.06$ (rms = 0.33 dex) and [Fe/H] $= -0.41 \pm 0.06$ (rms = 0.36 dex) on Zinn & West and Carretta & Gratton metallicity scales, respectively, consistent with the cluster metal abundance derived by Armandroff & Zinn. Most of the metallicities were extrapolated from calibration relations defined for [Fe/H] ≤ -1; however, they are clearly high and contrast with the rather long periods of the NGC 6441 variables, thus confirming that the cluster does not fit in the general Oosterhoff classification scheme. The rms scatter of the average is larger than observational errors (0.15–0.16 dex), possibly indicating some spread in metallicity. However, even the metal-poor variables, if confirmed to be cluster members, are still more metal-rich than those commonly found in the Oosterhoff type II globular clusters.

Subject headings: globular clusters: individual (NGC 6441) — stars: abundances — stars: horizontal-branch — stars: variables: other — techniques: spectroscopic

1. INTRODUCTION

NGC 6441 as well as its twin NGC 6388 are metal-rich, massive globular clusters ([Fe/H] $= -0.53 \pm 0.11$ and -0.60 ± 0.15, respectively; Armandroff & Zinn 1988) with very unusual horizontal branches (HBs) extending from stubby red, as expected for their high metallicities, to extremely blue, and with the red HBs sloping upward as one moves blueward in the V, $B-V$ color-magnitude diagram (Rich et al. 1997; Pritzl et al. 2001, 2002, 2003). Given their high metallicities, we would expect them to have very few RR Lyrae stars with the short periods typical of the Oosterhoff type I systems (Oosterhoff 1939). Rather unexpectedly, large numbers of RR Lyrae stars with unusually long periods, even longer than those commonly observed in the Oosterhoff type II systems, have been discovered in both clusters (Layden et al. 1999; Pritzl et al. 2001, 2002, 2003). Indeed, NGC 6441 and NGC 6388 seem to violate the trend of decreasing period with increasing metallicity followed by the Galactic globular clusters (GCs), and stand apart in the mean period versus [Fe/H] diagram (Pritzl et al. 2001). The clusters have been suggested to be a further and extreme manifestation of the so-called second-parameter effect, meaning that metallicity is not the only factor governing the morphology of the HB, but that other parameters such as age, helium or CNO abundances, core rotation, or dynamical interactions are at work. Some of these possibilities (e.g., a high helium abundance, higher interaction rates, etc.) are not supported by observations of NGC 6441 and NGC 6388 (Rich et al. 1997; Layden et al. 1999; Raimondo et al. 2002; Moehler et al. 1999). Thus, we still lack a satisfactory explanation for the cluster's peculiar HBs and for the unusual properties of their RR Lyrae stars.

A metallicity spread, as first argued by Piotto et al. (1997) from the intrinsic spread in color of the red giant branch, with the RR Lyrae stars and the blue HB stars being at the metal-poor tail ([Fe/H] $\lesssim -1.6$) of the cluster's metallicity distributions, could in principle explain their anomalous HBs (Sweigart 2002; Ree et al. 2002). In this scenario, NGC 6441 and NGC 6388, the two most massive Galactic GCs after ω Cen and M54, have been suggested to be the relics of disrupted dwarf galaxies (Ree et al. 2002), similar to ω Cen, which has a metallicity spread, and to M54, which is considered the nucleus of the Sagittarius galaxy (Layden & Sarajedini 2000). However, even the metallicity spread does not completely explain the unusual nature of NGC 6441 and NGC 6388 RR Lyrae stars (see discussions in Pritzl et al. 2001, 2002). On the other hand, if the RR Lyrae stars in NGC 6388 and NGC 6441 are metal-rich, they would form a new, distinct subclass of long-period, metal-rich RR Lyrae stars (Layden et al. 1999) that has no counterpart among the field and cluster RR Lyrae stars known so far, except perhaps V9 in 47 Tuc (Carney et al. 1993).

No direct measure of the metal abundance of the RR Lyrae stars in either cluster existed so far. Pritzl et al. (2001, 2002) derived metallicities for some of the *ab*-type RR Lyrae stars in the two clusters, using the parameters of the Fourier decomposition of the light curve and the Jurcsik-Kovács method (Jurcsik & Kovács 1996; Kovács & Jurcsik 1997). They estimated average metal abundances of [Fe/H] $= -0.99$ and -1.21 for NGC 6441 and NGC 6388, respectively, that according to Jurcsik (1995) correspond to -1.3 and -1.4 on the Zinn & West (1984, hereafter ZW84) metallicity scale. These metallicities are much lower than the cluster metal abundances derived by Armandroff & Zinn (1988) but are close to the metallicity of Sweigart (2002) models, which yield a best-fitting model of NGC 6441 HB for a [Fe/H] ~ -1.4 and an α-enhancement of $[\alpha/\mathrm{Fe}] = +0.3$. However, given the uncertainty of the Jurcsik-Kovács method (see discussions in Di Fabrizio et al. 2005; Gratton et al. 2004, hereafter G04; and Clementini et al. 2005, hereafter C05), and the unusual nature of the NGC 6441 and NGC 6388 RR Lyrae

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TABLE 1
LINE INDICES AND METAL ABUNDANCES OF RR LYRAE STARS IN THE GLOBULAR CLUSTER NGC 6441

Star[a]	HJD (−2,400,000)	Type	K	Hδ	Hγ	Hβ	⟨H⟩	MI	[Fe/H] ZW84	[Fe/H] CG97	V_r (km s^{-1})	[Fe/H][b]
V37	52,850.6112	*ab*	0.325	0.216	0.213	0.193	0.207	1.66	−0.71	−0.44	+18	−0.95
V38	52,850.6112	*ab*	0.405	0.157	0.155	0.191	0.167	1.69	−0.68	−0.41	−7	−1.14
V41[c]	52,849.6208	*ab*	0.473	0.056	0.030	0.096	0.060	0.91	−1.37	−1.15	+4	...
V43	52,850.6112	*ab*	0.513	0.098	0.119	0.122	0.113	1.60	−0.76	−0.49	−4	−1.16
V49[d]	52,850.6112	*c*	0.202	0.253	0.220	0.199	0.224	0.90	−1.37	−1.15	+22	...
V51	52,850.6112	*ab*	0.283	0.265	0.270	0.236	0.257	1.94	−0.46	−0.11	−16	−0.84
V69	52,849.6208	*c*	0.300	0.294	0.260	0.260	0.271	2.29	−0.15	+0.16	−10	...
V71	52,850.6112	*c*	0.358	0.222	0.187	0.192	0.200	1.80	−0.58	−0.30	+10	...
V72	52,850.6112	*c*	0.191	0.340	0.349	0.275	0.321	1.72	−0.65	−0.38	−6	...
V74	52,849.6208	*c*	0.147	0.331	0.312	0.289	0.311	1.17	−1.14	−0.90	−7	...
V77	52,849.6208	*c*	0.284	0.275	0.298	0.220	0.264	2.05	−0.36	−0.07	−12	...
V78	52,849.6208	*c*	0.188	0.347	0.356	0.286	0.329	1.75	−0.63	−0.36	−12	...

[a] Identifiers are from the Sawyer-Hogg online catalog of variable stars in Galactic globular clusters, published by Clement et al. (2001).
[b] Pritzl et al. (2001).
[c] Layden et al. (1999) find that this star is ∼0.7 mag brighter and ∼0.3 mag redder than the other RR Lyrae stars and suggest its image is blended with a red companion. Pritzl et al. (2001) agree on this hypothesis. The star is in the cluster central region, and from our spectrum it looks cooler than a normal RR Lyrae star (see Fig. 1), as also demonstrated by its rather small ⟨H⟩ value, thus supporting the blend hypothesis.
[d] This star is a suspected binary system for Layden et al. (1999). However, Pritzl et al. (2001) find it is a slightly overluminous *c*-type RR Lyrae. The star spectrum shows typical features of an RR Lyrae star (see Fig. 1) confirming Pritzl et al. (2001) classification.

stars, there is some question as to the validity of these metallicity determinations.

In this Letter we present the first direct measure of metallicity for RR Lyrae stars in NGC 6441 through spectroscopy, and provide the first quantitative assessment that the cluster variables are indeed metal-rich, with a few outliers possibly suggesting some spread in metallicity.

2. THE DATA

Spectra of 12 RR Lyrae stars in NGC 6441 were obtained in 2003 July in the course of a spectroscopic survey of RR Lyrae stars in the Sculptor dwarf spheroidal galaxy (C05). Observations

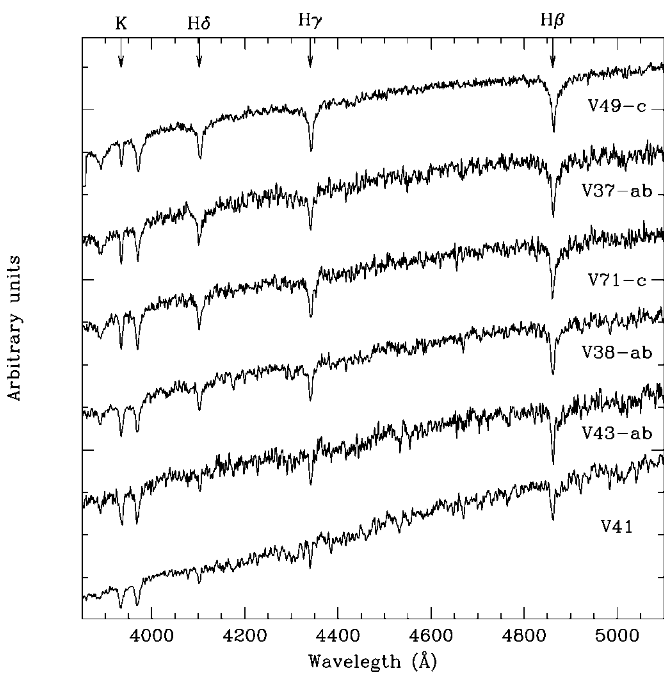

FIG. 1.—Examples of spectra of variable stars in NGC 6441 obtained using FORS2. The spectra have been offset for clarity, and the main spectral lines are indicated. They all correspond to variable stars having ⟨H⟩ < 0.25. V41 is very likely the blend of an RR Lyrae star with a cooler companion.

were performed using the FORS2 spectrograph at the ESO Very Large Telescope (VLT; Paranal, Chile). We observed two 6′.8 × 6′.8 FORS2 subfields of NGC 6441, centered at $\alpha_{2000} = 17^h50^m19^s.9$, $\delta_{2000} = -37°05'21''.9$ and $\alpha_{2000} = 17^h50^m24^s.5$, $\delta_{2000} = -37°00'06''.3$, and comprising five and seven RR Lyrae stars, respectively. Spectra were collected using slits 1″ wide and about 14″ long to allow for sky subtraction. With this configuration, each pixel corresponds to 0.75 Å. Our wavelength range contains both the Ca II K and the hydrogen Balmer lines up to Hβ. Exposure time was 300 s, as an optimal compromise between signal-to-noise ratio and time resolution of the light curve. Details on the observations and data-reduction procedures can be found in C05.

Time-series photometry for all the target stars, and the classification in types, has been published by Layden et al. (1999) and Pritzl et al. (2001). Accordingly, our sample includes five *ab*-type and seven *c*-type RR Lyrae stars; their identification is provided in Table 1. Figure 1 shows examples of spectra for some of the variable stars in the cluster.

We estimated radial velocities from our spectra; they are given in column (12) of Table 1. According to C05, typical errors of these radial velocity determinations are of about 15 km s^{-1}. Our radial velocity estimates do not exclude the cluster membership for any of the RR Lyrae stars we have analyzed. The 12 stars have $\langle v_r \rangle = -1$ km s^{-1} (rms = 12 km s^{-1}, and a zero-point error of ±7 km s^{-1}). Our average radial velocity differs somewhat from the value of +16.4 km s^{-1} (Harris 1996, online catalog).[6] A reason for part of this discrepancy is that our mean value includes the phase-dependent contributions due to the star pulsations. Further residual differences may be due to systematic offsets possibly caused by offcentering of the cluster variables on the slits.

3. MEASURE OF THE METAL ABUNDANCES

Metal abundances for the RR Lyrae stars in NGC 6441 were derived using a modified (and improved) version of the Δ*S* method (Preston 1959). Our technique is fully described in G04 and is based on the definition of hydrogen and Ca II spectral indices, ⟨H⟩ and K, for each variable star by directly integrating

[6] Available at http://www.physics.mcmaster.ca/Globular.html.

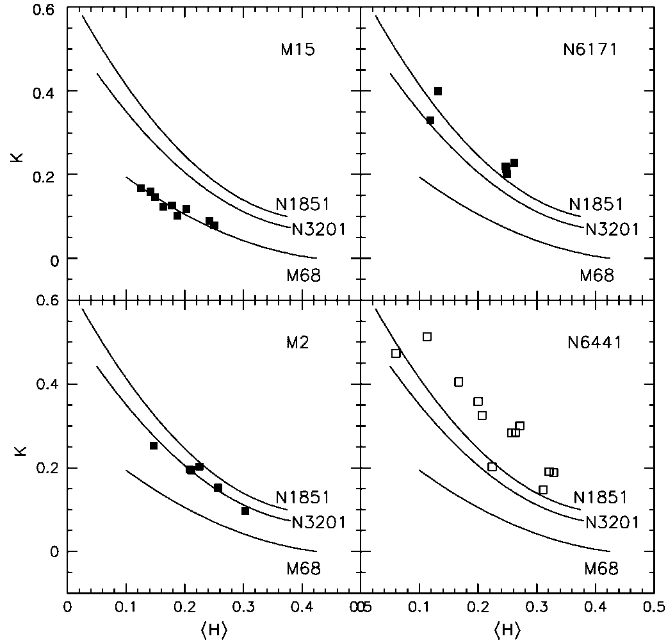

FIG. 2.—Correlations between K and ⟨H⟩ spectral indices for the calibrating clusters M15, M2, and NGC 6171 (from C05; *filled squares*) and M68, NGC 3201, and NGC 1851 (from G04; *solid lines*). For a definition of the spectral indices, see G04.

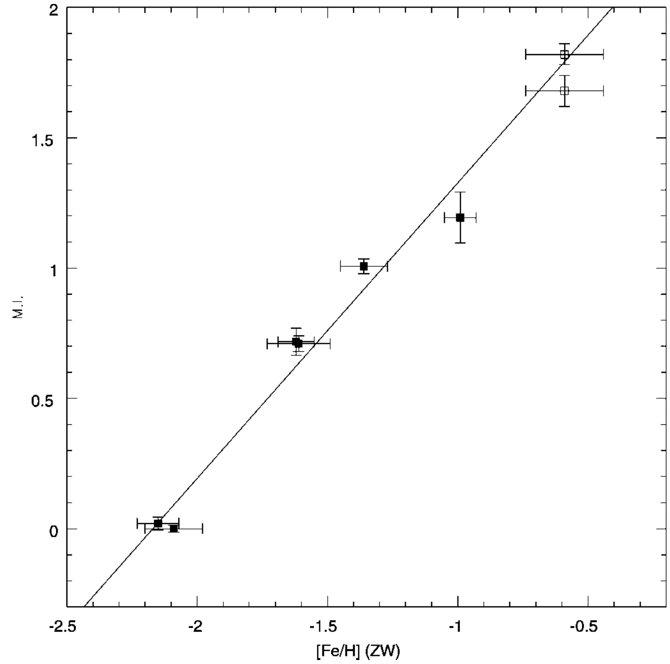

FIG. 3.—Calibration of the metallicity index on the ZW84 metallicity scale. Open squares represent NGC 6441, which is plotted according to its metallicity from ZW84 ([Fe/H] $= -0.59$) and the MI values obtained, both averaging all the 11 variable stars (*lower open square*) and discarding the two metal-poor objects V49 and V74 (*upper open square*). In both cases the cluster lies very close to the calibration line, which is based on the other clusters only, and perfectly falls on it if V49 and V74 are disregarded.

the instrumental fluxes in spectral bands centered on the Hδ, Hγ, Hβ, and Ca II K lines. These spectral indices are then used to measure metallicities by a comparison to the same quantities for variable stars in a number of globular clusters with known metal abundances. A summary of the method and an update of the metallicity calibration procedure can be found in C05. An advantage of our technique is that we do not need to know the phases of our spectra. On the other hand, the accuracy of our [Fe/H] may be a function of phase, as represented by the strength of the H lines. According to Figure 12 of G04, most accurate metallicity determinations are obtained for values of $\langle H\rangle < 0.20$ and 0.25 for *ab*- and *c*-type RR Lyrae stars, respectively. Outside these ranges, metal-abundance determinations may be more uncertain, depending on the actual value of ⟨H⟩. However, metallicities of individual stars in the calibrating clusters (see Tables 3 and 4 in G04, and Tables 5, 6, and 7 in C05) show this effect to be small, if present. This point is particularly relevant for the NGC 6441 RR Lyrae stars for which, based on the available photometric data (Layden et al. 1999; Pritzl et al. 2001) it may be difficult to reliably define the pulsation phase at the epochs of the observations. Line indices measured for the RR Lyrae stars in NGC 6441 are provided in columns (4) to (8) of Table 1. The stellar K values were not corrected for the interstellar K-line contribution, since we estimated it to be much less than 0.1 dex in [Fe/H]. In fact, given the small absolute value of the cluster radial velocity, interstellar lines are expected to lie in the core of the stellar K lines, where there is almost no flux, and then they can subtract only a negligible fraction of flux.[7] This would not be the case for halo stars where, due to the high velocities, the interstellar absorptions occur outside the line cores.

The calibration of the line indices of the variable stars in terms of metal abundances [Fe/H] was obtained using RR Lyrae stars observed in the clusters M15, M2, and NGC 6171 (C05) and M68, NGC 1851, and NGC 3201 (G04). For all these clusters, precise metal abundances are available on both the ZW84 and the Carretta & Gratton (1997, hereafter CG97) metallicity scales. Figure 2 shows the correlation between K and ⟨H⟩ indices for the calibrating clusters, and in the bottom right panel, the position on the K versus ⟨H⟩ plane of the NGC 6441 variable stars. The figure shows that there are three objects lying near the ridge line of NGC 1851 at an average metallicity of [Fe/H] $\simeq -1.3$ on the ZW84 scale, while all the remaining stars define a tight correlation at higher metallicity. However, one of the deviating objects, star V41, is probably blended with a cooler companion, as suggested by its spectrum (see Fig. 1). Thus, its metallicity is uncertain, and we drop it from any further consideration. V49 was observed in the safe range in which metal abundance determinations are most reliable. The spectrum of this star is shown in Figure 1, along with spectra of all the variables having $\langle H\rangle < 0.25$, and it clearly shows that the star has a shallower K line. Finally, V74 was observed at $\langle H\rangle = 0.311$, thus its metallicity may be slightly more uncertain.

Metallicity indices (MIs) for the program stars were derived from their K and ⟨H⟩ values using equations (3), (4), and (5) of G04. They are listed in column (9) of Table 1. Metal abundances [Fe/H] were then deduced from the MI values using the metallicity calibrations defined by C05. These are described by linear regressions, namely equations (4) and (5) of C05, between the average ⟨MI⟩ values of RR Lyrae stars in the calibrating clusters M15, M2, NGC 6171, M68, NGC 1851, and NGC 3201 and the cluster's metal abundances on the ZW84 and CG97 metallicity scales, respectively. In Figure 3 we show the calibration relation of the metallicity indices on the ZW84 metallicity scale. We note that the calibrating clusters have metallicities that do not extend higher than [Fe/H] ~ -1; thus,

[7] We checked this point on the spectra of a few NGC 6441 giants we recently observed with UVES at the VLT. We estimated that according to the definition of the spectral indices used in the present study, the interstellar K-line contribution may cause a systematic offset <0.02 dex in the metal abundance of the NGC 6441 variable stars.

the metal abundance we derive for NGC 6441 is an extrapolation of the calibration equations. However, the cluster is found to fall well on the extrapolation to higher metallicities of the linear relation defined by the calibrating clusters. This result is in agreement with the original Preston's ΔS method, which appears to have a linear calibration up to about solar metallicity.

Individual metal abundances derived with this procedure are given in columns (10) and (11) of Table 1. According to C05, we attach internal errors of 0.15 and 0.16 dex to individual abundance determinations on the ZW84 and CG97 scales, respectively. However, to take into account any additional uncertainty that might affect the spectra corresponding to $\langle H \rangle$ values outside the safest range, below we divide the stars in three groups corresponding to $\langle H \rangle \leq 0.224$, $0.257 \leq \langle H \rangle \leq 0.271$, and $0.311 \leq \langle H \rangle \leq 0.329$, and all averages are computed, giving different weights to the three groups of stars (i.e., 1, 0.75, and 0.5).

For comparison, in the last column of Table 1, we report the metal abundances derived by Pritzl et al. (2001) from the Fourier decomposition of the light curve for four of the *ab*-type RR Lyrae stars analyzed here. The average of Pritzl et al. (2001) values for the four stars is $[Fe/H] = -1.02$ (rms = 0.15), on the Jurcsik (1995) metallicity scale. According to equation (4) in Jurcsik (1995), this corresponds to $[Fe/H] = -1.33$ on the ZW84 scale. The average of our metal abundances for these four stars is $[Fe/H] = -0.67$ (rms = 0.11) on the ZW84 scale (i.e., much more metal-rich). This result seems to suggest that the Jurcsik-Kovács method may not be reliable when applied to the anomalous RR Lyrae stars in NGC 6441.

Adopting the averaging scheme described above, the mean metal abundance of our RR Lyrae sample in NGC 6441 is $[Fe/H] = -0.69 \pm 0.06$ (rms = 0.33 dex, 11 stars) and -0.41 ± 0.06 (rms = 0.36 dex) on the ZW84 and CG97 scales, respectively. The scatter of the average is larger than expected from measurement errors alone (<0.2 dex), thus suggesting that if the 11 variables are all cluster members, there is some spread in metallicity with two more metal-poor objects at an average metal abundance around $[Fe/H] \sim -1.3$, and the remaining nine more metal-rich stars around $[Fe/H] \sim -0.6$ dex (on the ZW84 scale). If the two metal-poor stars are disregarded, the mean metal abundances become $[Fe/H] = -0.57 \pm 0.04$ (rms = 0.19 dex, nine stars), and -0.28 ± 0.04 (rms = 0.21 dex). The former value is in excellent agreement with both ZW84 and Armandroff & Zinn (1988) metallicity estimates for the cluster.

4. SUMMARY AND CONCLUSIONS

Metal abundances from low-resolution spectroscopy obtained with FORS2 at the ESO VLT have revealed that the NGC 6441 RR Lyrae stars are metal-rich, with an average metal abundance of $[Fe/H] = -0.69 \pm 0.06$ on the ZW84 scale. The spectroscopic analysis also reveals that there are 2 variables (out of 11) having metallicities around $[Fe/H] \sim -1.3$. However, the metal-poor stars, if confirmed cluster members, are a minor component of our sample. Even allowing for measurement errors, we do not find in this cluster RR Lyrae stars as metal-poor as the variables commonly found in the Galactic Oosterhoff type II GCs, as instead one would expect from the extraordinarily long periods and the position near the Oosterhoff type II line of the NGC 6441 variables in the period-amplitude diagram (see Fig. 6 of Pritzl et al. 2003). Clearly, metal abundances and memberships for a larger number of variable stars are needed to better assess the metallicity distribution of the NGC 6441 stars and the relevance of the metal-poor component, if any. Nevertheless, the existence of extremely long period RR Lyrae stars with extraordinarily high metal abundances, as exhibited by some of the variables in our sample, demonstrates that the NGC 6441 variable stars are different from the RR Lyrae stars known so far both in the Milky Way GCs and in the field, and confirms that this cluster does not conform to the Oosterhoff dichotomy described by the other Galactic GCs.

Which mechanism may be able to produce such metal-rich variables with pulsation characteristics similar to the Oosterhoff type II ones remains unexplained. For instance, Pritzl et al. (2002) show that it is difficult to model NGC 6441 as an Oosterhoff type II system under the hypothesis that its variables are evolved from a position on the blue zero-age HB as a result of the small number of progenitors on the blue HB. As suggested by Layden et al. (1999) and Pritzl et al. (2001), the theoretical reproduction of the observed light curves with pulsation models may shed some light on the physical properties responsible for the anomalous properties of the NGC 6441 RR Lyrae stars. Such modeling for the variables analyzed in the present Letter is currently under way (G. Clementini & M. Marconi 2005, in preparation).

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REFERENCES

Armandroff, T. E., & Zinn, R. 1988, AJ, 96, 92
Carney, B. W., Storm, J., & Williams, C. 1993, PASP, 105, 294
Carretta, E., & Gratton, R. G. 1997, A&AS, 121, 95 (CG97)
Clement, C., et al. 2001, AJ, 122, 2587
Clementini, G., Ripepi, V., Bragaglia, A., Martinez Fiorenzano, A., Held, E. V., & Gratton, R. G. 2005, MNRAS, in press (astro-ph/0506206) (C05)
Di Fabrizio, L., Clementini, G., Maio, M., Bragaglia, A., Carretta, E., Gratton, R., Montegriffo, P., & Zoccali, M. 2005, A&A, 430, 603
Gratton, R. G., Bragaglia, A., Clementini, G., Carretta, E., Di Fabrizio, L., Maio, M., & Taribello, E. 2004, A&A, 421, 937 (G04)
Harris, W. E. 1996, AJ, 112, 1487
Jurcsik, J. 1995, Acta Astron., 45, 653
Jurcsik, J., & Kovács, G. 1996, A&A, 312, 111
Kovács, G., & Jurcsik, J. 1997, A&A, 322, 218
Layden, A. C., & Ritter, L. A., Welch, D. L., Webb, T. M. A. 1999, AJ, 117, 1313
Layden, A. C., & Sarajedini, A. 2000, AJ, 119, 1760
Moehler, S., Sweigart, A. V., & Catelan, M. 1999, A&A, 351, 519
Oosterhoff, P. Th. 1939, Observatory, 62, 104
Piotto, G., et al. 1997, in Advances in Stellar Evolution, ed. R. T. Rood & A. Renzini (Cambridge: Cambridge Univ. Press), 84
Preston, G. W. 1959, ApJ, 130, 507
Pritzl, B. J., Smith, H. A., Catelan, M., & Sweigart, A. V. 2001, AJ, 122, 2600
———. 2002, AJ, 124, 949
Pritzl, B. J., Smith, H. A., Stetson, P. B., Catelan, M., Sweigart, A. V., Layden, A. C., & Rich, R. M. 2003, AJ, 126, 1381
Raimondo, G., Castellani, V., Cassisi, S., Brocato, E., & Piotto, G. 2002, ApJ, 569, 975
Ree, C. H., Yoon, S.-J., Lee, S.-C., & Lee, Y.-W. 2002, in ASP Conf. Ser. 265, Omega Centauri: A Unique Window into Astrophysics, ed. F. van Leeuwen, J. D. Hughes, & G. Piotto (San Francisco: ASP), 101
Rich, R. M., et al. 1997, ApJ, 484, L25
Sweigart, A. V. 2002, Highlights Astron., 12, 292
Zinn, R., & West, M. J. 1984, ApJS, 55, 45 (ZW84)