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RR LYRAE VARIABLES IN THE GLOBULAR CLUSTER M55. THE FIRST EVIDENCE FOR NONRADIAL PULSATIONS IN RR LYRAE STARS[1]

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ABSTRACT

We present the results of a photometric study of RR Lyrae variables in the field of the globular cluster M55. We have discovered nine new RR Lyrae stars, increasing the number of known RR Lyrae variables in this cluster to 15 stars. Five of the newly discovered variables are Bailey type RR*c*, and two are type RR*ab*. Two background RR*ab* stars are probable members of the Sagittarius dwarf galaxy. Fourier decomposition of the light curves was used to derive basic properties of the present sample of RR Lyrae variables. From an analysis of the RR*c* variables we obtain a mean mass of $M = 0.53 \pm 0.03\ M_{\odot}$, luminosity $\log L = 1.75 \pm 0.01$, effective temperature $T_{\rm eff} = 7193 \pm 27$ K, and helium abundance $Y = 0.27 \pm 0.01$. Based on the $B-V$ colors, periods, and metallicities of the RR*ab* stars, we estimate the value of the color excess for M55 to be equal to $E(B-V) = 0.11 \pm 0.03$. Using this value we derive the colors of the blue and red edges of the instability strip in M55. The blue edge lies at $(B-V)_0 = 0.20$ mag, and the red edge lies at $(B-V)_0 = 0.38$ mag. We estimate the values of the visual apparent distance moduli to be 13.65 ± 0.11 from RR*ab* stars and 13.91 ± 0.08 from RR*c* stars. The light curves of three of the RR*c* variables exhibit changes in amplitude of over 0.1 mag on the timescale of less than a week, rather short for the Blazhko effect, but with no evidence for another radial pulsational frequency. However, we do detect other periodicities for these three stars that are clearly visible in the light curve after removing variations with the first overtone radial frequency. This is strong evidence for the presence of nonradial pulsations, a behavior common for δ Scuti stars but not yet observed among RR Lyrae variables.

Key words: globular clusters: individual (M55) — RR Lyrae variable — stars: variables: general

1. INTRODUCTION

M55 (=NGC 6809 = C1936−310) is a metal-poor halo globular cluster that is both luminous and relatively easy to study due to its proximity and low concentration. Its reddening and apparent distance moduli are estimated at $E(B-V) = 0.07$ and $(m-M)_V = 13.76$ (Harris 1996). This cluster was selected as one of the targets in an ongoing survey for eclipsing binaries in globular clusters (e.g., Kaluzny, Thompson, & Krzeminski 1997; Thompson et al. 1999). As a side result of this survey we have obtained extensive time series photometry for several RR Lyrae stars belonging to M55. More than half of these variables are new discoveries. This contribution is devoted exclusively to the presentation and analysis of photometry of M55 RR Lyrae variables from the cluster field. Results obtained for other variables will be published elsewhere (Thompson et al. 1999).

2. OBSERVATIONS AND DATA REDUCTION

Time series photometry of M55 was obtained during the interval 1997 May 9–September 17 with the 1.0 m Swope Telescope at Las Campanas Observatory. The CCD camera used for the observations has a field of view of $14'.5 \times 23'$ with a scale of $0''.435$ pixel^{-1} (for reference, the tidal radius of M55 is $18'.6$ [Peterson & King 1975]). More than 700 *V*-band frames and 65 *B*-band frames were obtained with exposure times ranging from 150 to 300 s for the *V* filter and 200 to 360 s for the *B* filter, depending on the seeing. Instrumental photometry was measured using DoPHOT (Schechter, Mateo, & Saha 1993), and the transformation to the standard *BV* system was based on observations of several Landolt fields (Landolt 1992). A more detailed description of the observations and reductions can be found in a complementary paper presenting results for eclipsing binaries and SX Phe stars identified in M55 (Thompson et al., in preparation).

3. RESULTS

This search for variable stars in M55 has identified 15 RR Lyrae variables. Six of them (stars V1–V6 from Sawyer Hogg 1973) were previously known (Bailey 1902; King 1951; King & Bruzual 1976). Of the remaining nine newly discovered variables, five are type RR*c* and four are type RR*ab*.

The equatorial coordinates, periods, intensity averaged *V* brightnesses, $\langle B \rangle - \langle V \rangle$ colors, *V* amplitudes, and types of the 15 RR Lyrae variables are listed in Table 1. The variables are designated according to the specifications of Task Group on Designations of IAU Commission 5. The stars NGC 6809 Saw V1 through NGC 6809 Saw V6 are from Sawyer Hogg (1973), and the stars NGC 6809 LCO V7 through NGC 6809 LCO V15 are new discoveries. Hereafter we use the designations V1–V15. A color-magnitude diagram of M55 derived from our observations is presented in Figure 1. Open circles denote the RR*c* stars, and filled circles correspond to the RR*ab* variables belonging to M55.

[1] Based on observations collected at the Las Campanas Observatory of the Carnegie Institution of Washington.

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TABLE 1

ELEMENTS OF THE RR LYRAE VARIABLES IN M55

Star	R.A. (J2000.0)	Decl. (J2000.0)	P (days)	⟨V⟩	⟨B⟩ − ⟨V⟩	A_V	Type
V1	19 40 22.45	−30 58 24.28	0.579978	14.38	0.36	1.28	RR*ab*
V2	19 39 42.24	−30 57 57.47	0.406147	14.41	0.39	0.44	RR*c*
V3	19 40 05.27	−31 02 34.50	0.661987	14.28	0.40	0.85	RR*ab*
V4	19 40 07.43	−30 56 32.11	0.384164	14.33	0.39	0.40	RR*c*
V5	19 39 55.89	−30 58 44.42	0.376146	14.32	0.37	0.43	RR*c*
V6	19 40 07.69	−30 57 49.96	0.388821	14.38	0.39	0.47	RR*c*
V7	19 39 59.89	−30 57 33.08	0.682573	14.26	0.46	1.03	RR*ab*
V8	19 40 02.08	−30 58 58.43	0.721961	14.37	0.49	0.62	RR*ab*
V9	19 40 27.38	−30 57 59.07	0.316307	14.43	0.31	0.41	RR*c*
V10......	19 40 08.51	−30 54 49.04	0.331763	14.41	0.32	0.31	RR*c*
V11......	19 40 12.02	−30 56 14.06	0.309954	14.42	0.31	0.21	RR*c*
V12......	19 39 59.80	−30 58 02.73	0.325864	14.34	0.32	0.26	RR*c*
V13......	19 39 53.08	−30 50 30.57	0.397841	14.44	0.34	0.39	RR*c*
V14......	19 39 54.76	−30 50 10.17	0.521616	17.97	0.43	1.03	RR*ab* Sgr
V15......	19 39 43.95	−31 00 36.33	0.637286	18.33	0.42	0.40	RR*ab* Sgr

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

The filled triangles correspond to two RR*ab* stars that are more distant than M55 by about 3.5 mag. These two variables are most likely members of the Sagittarius dwarf galaxy (Ibata, Gilmore, & Irwin 1994). The presence of a noticeable population of stars belonging to the Sagittarius dwarf in the field of M55 has been noted by Mateo & Mirabel (1996) and Fahlman et al. (1996). Mateo & Mirabel reported the identification of three RR Lyrae stars from the Sagittarius dwarf in their survey for variables in M55, and it is likely that the two distant RR*ab* stars discovered by us are among these variables. The periods of the cluster RR*c* stars are between 0.310 and 0.406 days with a mean period of 0.36 days. The periods of the cluster RR*ab* variables are between 0.580 and 0.722 days with a mean value of 0.66 days. These properties clearly place M55 among the Oosterhoff type II clusters. Finding charts for the newly discovered RR Lyrae stars are given in Figure 2.

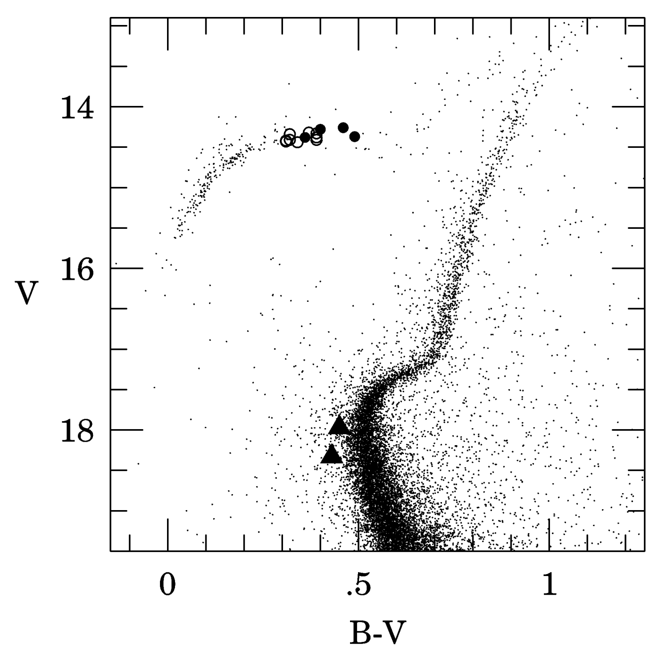

FIG. 1.—Color-magnitude diagram of M55. The filled circles, open circles, and triangles denote RR*ab* and RR*c* stars from M55 and RR*ab* variables from the Sagittarius dwarf galaxy, respectively.

We have fitted our *V*-band light curves to Fourier series with the form

$$V = A_0 + \sum_{j=1}^{10} A_j \sin(j\omega t + \phi_j) , \qquad (1)$$

where $\omega = 2\pi/P$ and P is the pulsation period of the star. A method developed by Schwarzenberg-Czerny (1997) was used to determine values of ω, A_j, and ϕ_j. Although the formal errors of our periods from a least-squares fit are quite small, we estimate their actual value to be as large as 0.000010 days. This is caused by correlations of residuals not accounted for in the least-squares solution. Our estimate for the errors in the derived periods corresponds to a phase uncertainty of 0.01P over the entire length of the observations, a reasonable value given the quality of our light curves. The magnitude of the uncertainty in the period is in agreement with the scatter of periods obtained by fitting Fourier series with different numbers of harmonics.

In Figures 3, 4, and 5, we show V, B, and $B-V$ light curves of the M55 RR*ab* stars, the M55 RR*c* stars, and the RR*ab* stars from the Sagittarius dwarf galaxy, respectively. The $B-V$ colors of each star were derived from equation (1) by calculating the V brightness at the epoch of each of the B observations.

The values of the peak-to-peak amplitudes A_V presented in Table 1 are used to plot the period-amplitude diagram shown in Figure 6. Again, open circles denote RR*c* stars, filled circles RR*ab* stars, and filled triangles the two Sagittarius dwarf RR*ab* stars identified in the field of M55. The solid line represents a linear fit to RR*ab* variables in M3 (Kaluzny et al. 1998). The data presented in Figure 6 agree with the well-established fact that the metallicity of M55 is lower than the metallicity of M3. At the same time the metallicities of the two RR*ab* stars from the Sagittarius dwarf are likely to be slightly higher than the metallicity of M3.

3.1. *A Fourier Analysis of the RRc Variables*

In a series of papers Simon & Teays (1982), Simon (1989), and Simon & Clement (1993) have presented a method of

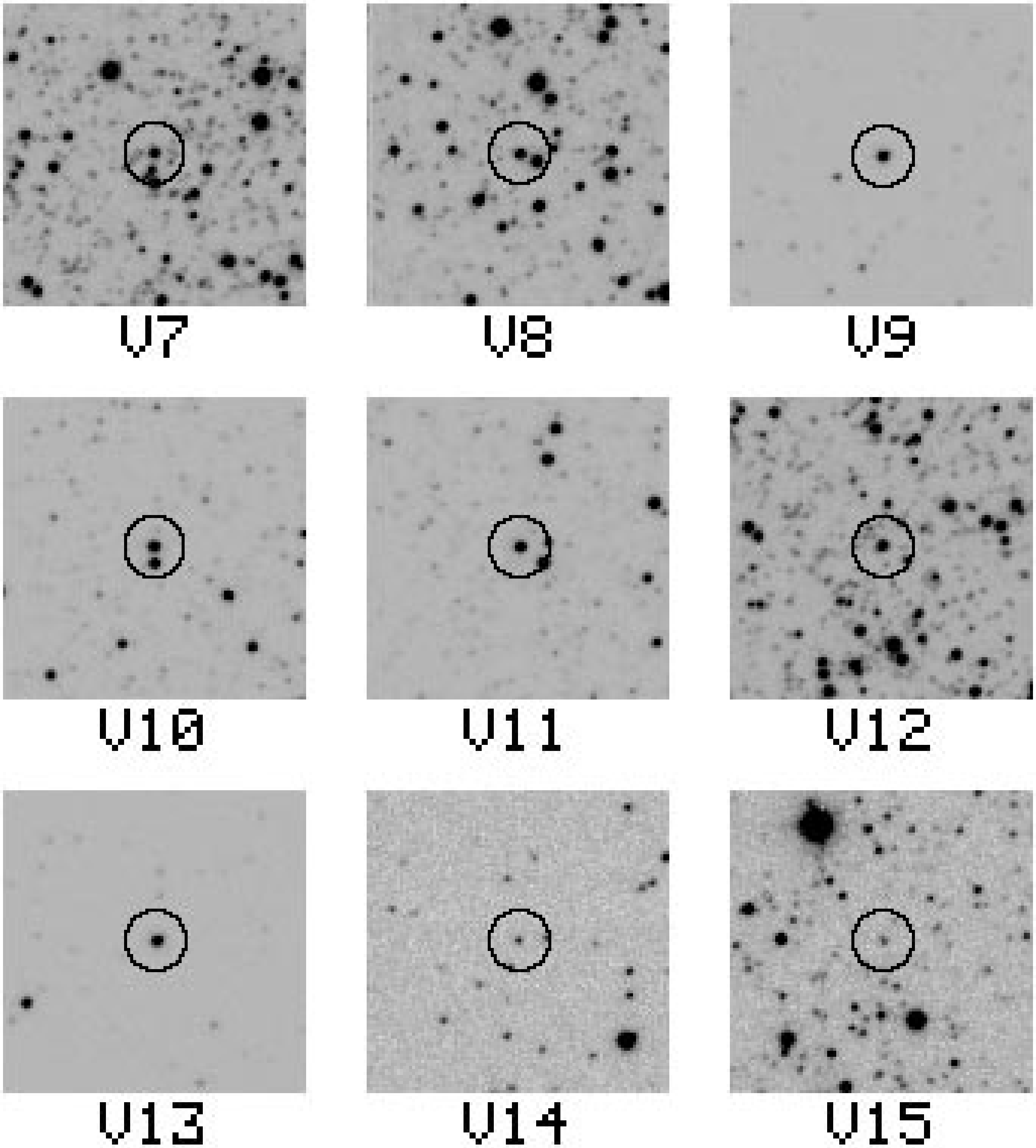

FIG. 2.—Finding charts for the newly discovered RR Lyrae stars in M55. Each chart is 1 arcmin^2, with north at the top and east to the left.

estimating the masses, luminosities, effective temperatures, and the helium abundance of RR*c* stars based only on a Fourier decomposition of the V-band light curves. The equations of Simon & Clement (1993) are

$$\log M = 0.52 \log P_1 - 0.11\phi^*_{31} + 0.39 , \quad (2)$$

$$\log L = 1.04 \log P_1 - 0.058\phi^*_{31} + 2.41 , \quad (3)$$

$$\log T_{\rm eff} = 3.265 - 0.3026 \log P_1 - 0.1777 \log M + 0.2402 \log L , \quad (4)$$

$$\log Y = -20.26 + 4.935 \log T_{\rm eff} - 0.2638 \log M + 0.3318 \log L , \quad (5)$$

$0.01{\cdot}P$ where M is the mass of the star in solar units, P_1 is the first overtone pulsation period in days, L is the luminosity in solar units, $T_{\rm eff}$ the effective temperature in Kelvins, and $\phi^*_{31} = \phi^*_3 - 3\phi^*_1$. The phases marked by an asterisk are obtained from a cosine Fourier series (used by Simon & Clement 1993) and differ from our phases, which were obtained from a sine series (cf. eq. [1]). For ϕ_{31} we have $\phi_{31} = \phi^*_{31} + \pi$.

Using the above equations we computed the masses, luminosities, and effective temperatures of the RR*c* stars in our sample. These are presented in Table 2 together with the values of A_0, A_1, and ϕ^*_{31}. The errors presented in Table 2 are calculated from the formal errors in the Fourier coefficients.

We exclude from our sample variables V9, V10, and V12 due to their irregular light curves (see § 3.2 for a detailed discussion). We also omit variable V11 due to the low accu-

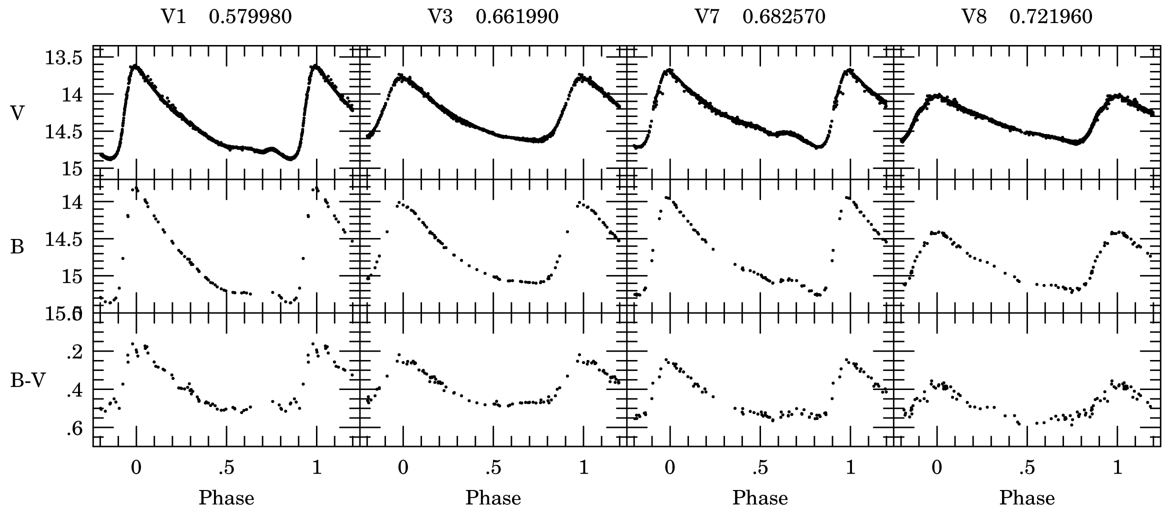

FIG. 3.—V, B, and $B-V$ light curves of RR*ab* Lyr stars from M55

racy of the estimation of ϕ^*_{31}. The mean values of the mass, luminosity, effective temperature, and helium abundance for the remaining five RR*c* variables are $0.53 \pm 0.03\ M_\odot$, $\log L/L_\odot = 1.75 \pm 0.01$, $T_{\rm eff} = 7193 \pm 27$ K, and $Y = 0.27 \pm 0.01$, respectively. These values are broadly consistent with those for the RR*c* variables in the sequence of globular clusters discussed by Kaluzny et al. (1998, cf. their Table 4).

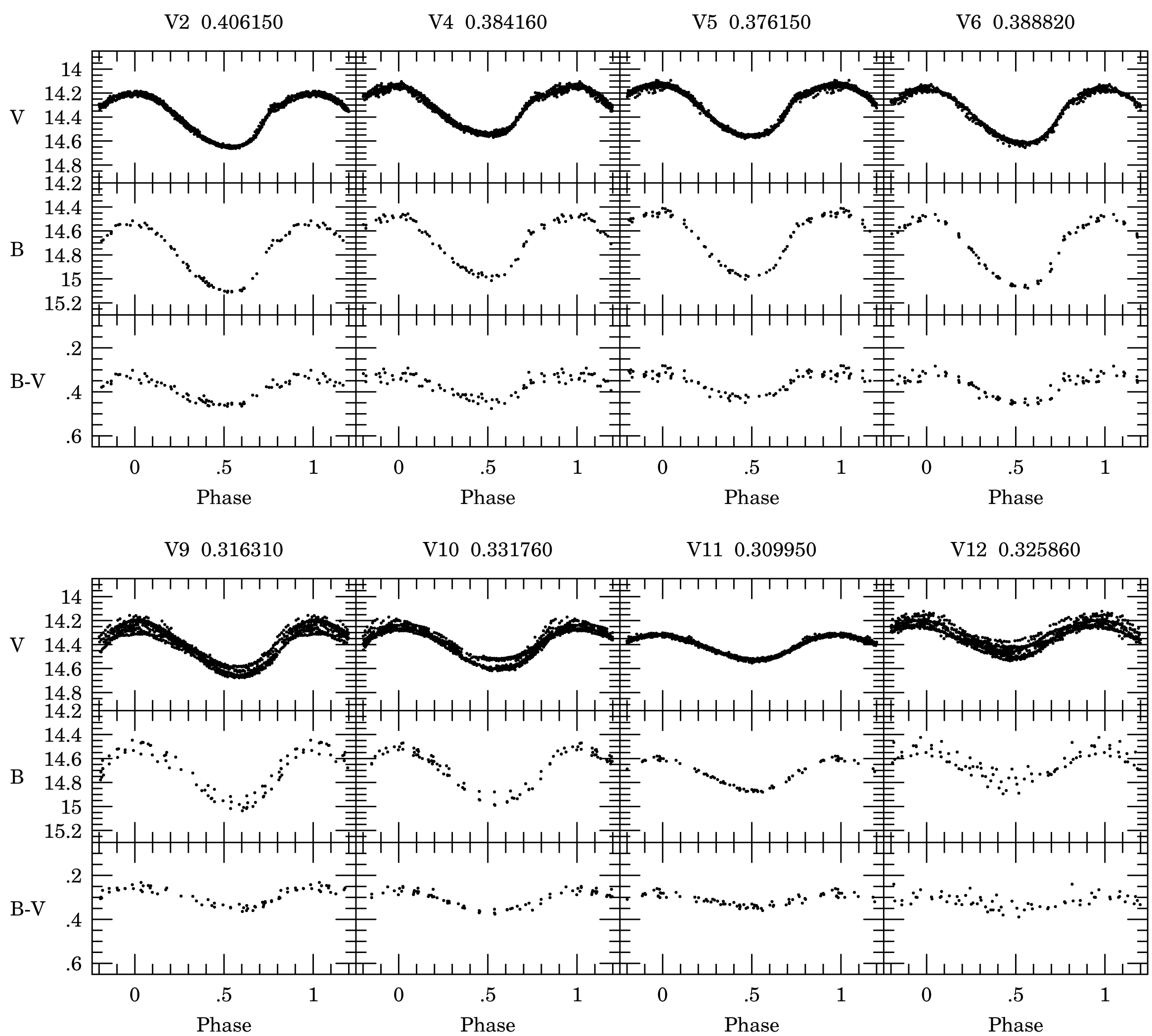

FIG. 4.—V, B, and $B-V$ light curves of RR*c* Lyr stars from M55

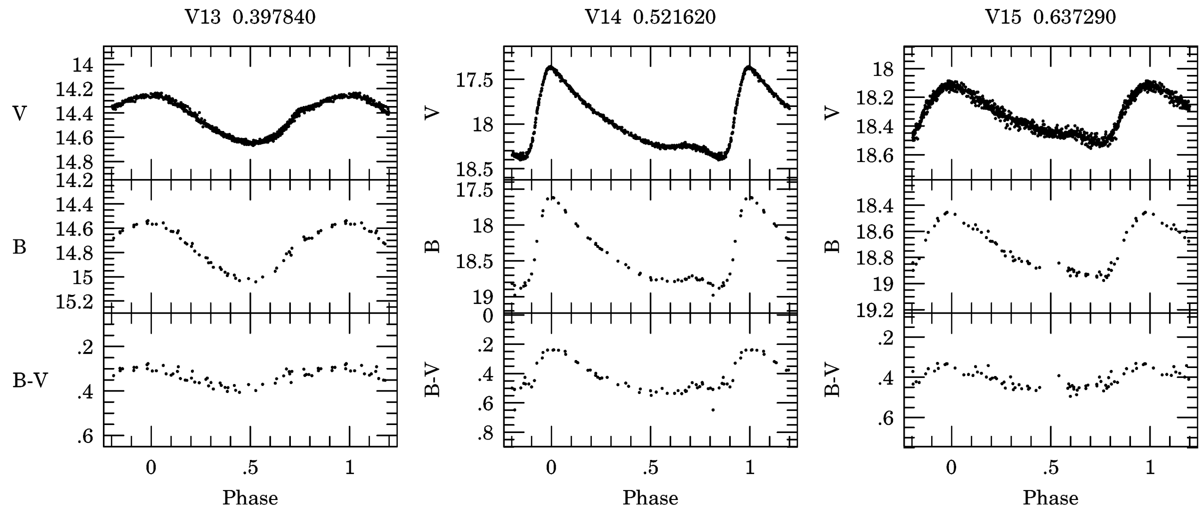

FIG. 5.—V, B, and $B-V$ light curves of RR*c* Lyr star from M55 and two RR*ab* Lyrae stars from Sagittarius dwarf galaxy

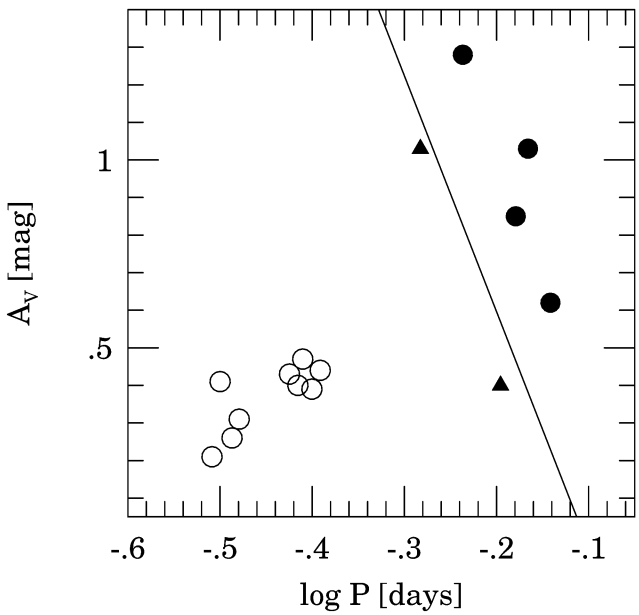

FIG. 6.—Period-amplitude diagram from RR*ab* stars from M55 (*filled circles*), RR*c* stars from M55 (*open circles*), and RR*ab* stars from Sagittarius Dwarf Galaxy (*triangles*). The solid line represents a linear fit to RR*ab* variables in M3 (Kaluzny et al. 1998).

Previous determinations of the metallicity of M55 vary between -1.54 (Bica & Pastoriza 1983; Pilachowski 1984; Smith 1984) and -1.96 (Minniti et al. 1993). The lower estimates agree with recent ones of Suntzeff, Kinman, & Kraft (1991) who obtained [Fe/H] $= -1.81$; McWilliam, Geisler, & Rich (1992) who obtained [Fe/H] $= -1.91$; and Geisler, Minniti, & Claria (1992) who obtained [Fe/H] $= -1.95 \pm 0.1$. Considering that the values of log L, $T_{\rm eff}$, and Y obtained from the RR*c* stars are consistent with the sequence from Kaluzny et al. (1998), we conclude that this analysis supports the more metal-poor determinations of [Fe/H] for M55.

However, the Fourier analysis suggests a mean mass for the M55 RR*c* stars that is discrepant with the Kaluzny et al. (1998) sequence. Our mean value is 0.53 ± 0.03 $M_{\odot}$. It places M55 between globular clusters such as NGC 6171 ([Fe/H] $= -0.68$, log $L = 1.65$, and $T_{\rm eff} = 7447$ K) and M5 ([Fe/H] $= -1.25$, log $L = 1.68$, and $T_{\rm eff} = 7388$ K). These values disagree markedly with the values determined in this present work.

Table 2 also contains the values of the absolute magnitudes M_V of the RR*c* variables in M55. These magnitudes were calculated from log $L/L_{\odot}$, assuming a value of 4.79 for $M_{\rm bol}$ of the sun and using a bolometric correction BC $= 0.06$[Fe/H] $+ 0.06$, adopted from Sandage & Cac-

TABLE 2

PARAMETERS FOR THE RR*c* VARIABLES IN M55

Star	A_0	A_1	ϕ_{31}	M	log L	$T_{\rm eff}$
V2	14.418	0.228	4.089	0.545	1.766	7150
	±0.000	±0.001	±0.039	±0.005	±0.002	±3
V4	14.342	0.203	4.216	0.513	1.733	7220
	±0.001	±0.001	±0.049	±0.006	±0.003	±4
V5	14.335	0.223	3.947	0.543	1.739	7217
	±0.000	±0.001	±0.042	±0.006	±0.002	±3
V6	14.363	0.234	3.847	0.567	1.760	7173
	±0.001	±0.001	±0.074	±0.011	±0.004	±6
V11	14.423	0.105	3.448	0.557	1.681	7375
	±0.000	±0.000	±0.306	±0.043	±0.018	±28
V13	14.445	0.195	4.448	0.493	1.736	7205
	±0.001	±0.001	±0.059	±0.007	±0.003	5

ciari (1990). Assuming [Fe/H] $= -1.8$, the mean value of the absolute magnitude M_V for RR*c* variables with $\sigma_{\phi_{31}^*} < 0.1$ is 0.47 ± 0.08, in excellent agreement with recent the estimate of Mandushev et al. (1996), who derived $M_V = 0.45 \pm 0.13$ from main-sequence fitting. Using this value of M_V and our measured mean value of $A_0 = 14.38$ we compute a mean apparent distance modulus of $(m - M)_V = 13.91 \pm 0.08$. This is also in excellent agreement with the estimate of Mandushev et al. (1996), who derived $(m - M)_V = 13.90 \pm 0.09$. Once again, this result for the absolute magnitudes of the M55 RR*c* stars is consistent with the sequence of clusters discussed by Kaluzny et al. (1998) but of course is in substantial disagreement with estimates based on Baade-Wesselink observations for RR*ab* stars (Carney, Storm, & Jones 1992; see § 3.3).

Although Walraven (1953) suspected a relation between the Fourier coefficients of the light curves and stellar parameters for RR Lyr stars, this was first demonstrated for RR*c* stars by the models of Simon & Teays (1982) and refined by Simon & Clement (1993). Their results have motivated a considerable observational effort, including this work. In an attempt to check the consistency of models and observations, Simon & Clement (1993) plotted luminosities derived from equation (3) against V and found a poor correlation, except for the cluster ω Cen. Figure 7 presents a similar plot for M55. The solid lines have a slope of 0.4 and are separated by 0.04 in log L, which represents the uncertainty in the values of log L computed from ϕ_{31}^* and P_1 (Simon & Clement 1993). It is clear that our points do not show a good correlation. Consistency of the estimated masses, temperatures, and luminosities depends to a lesser degree on small observational errors and to a large degree on systematic differences between the Simon & Clement (1993) models and observations.

For many reasons one should expect systematic differences between relations based on state-of-the-art models (e.g., eqs. [2]–[5]) and observations, both as in Figure 7 for M55 and for other clusters (Kovacs & Kanbur 1998). Such computational problems as the treatment of convection and of radiative transfer in atmospheres seriously affect the internal agreement between model calculations (e.g., Feuchtinger & Dorfi 1997; Bono et al. 1997). Unknown sources of discrepancies between models and observations may be hidden in the physics of these stars. For example, we may observe stars on different crossings of the instability strip or stars for which the light curves are still evolving on growth timescales much longer than covered by our observations (unsaturated pulsation modes). One might suspect observational problems as well. Kovacs & Kanbur (1998) argue that errors in bolometric corrections could produce errors of 0.1 mag and 0.2 rad in A_1 and ϕ_{21}. However, these errors cause only small differential effects in a plot such as Figure 7. Simon & Clement (1993) postulated problems with dense field photometry as a source of scatter in the log L–$\langle V \rangle$ plot. We can exclude any major influence of this effect in our photometry. A comparison of the photometry of main-sequence turnoff stars located in the central regions of the cluster with photometry for similar stars at the periphery of the cluster reveals no systematic differences larger than 0.05 mag. Since RR*c* stars lie 3 mag above the main-sequence turnoff, we expect systematic errors in V for these stars to be less than 0.01 mag.

Noting from equations (2)–(5) that log M, log L, log $T_{\rm eff}$, and log Y all are linear functions of log P_1 and ϕ_{31}^*, we observe that their averages contain no more information than the average values of log P_1 and ϕ_{31}^*, -0.425 ± 0.017 and 4.00 ± 0.14, respectively. Hence, these values may be convenient model independent characteristics of the cluster.

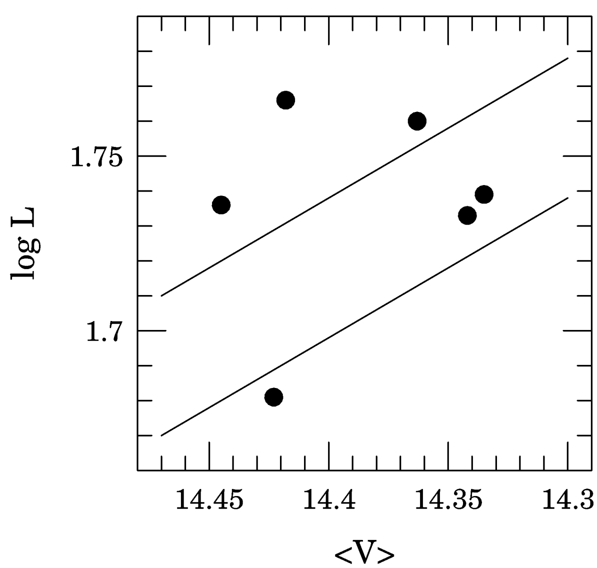

FIG. 7.—Dependence between derived luminosity and visual magnitude for the RR*c* stars in M55. The solid lines have a slope of 0.4 and are separated by 0.04 in log L, which represents the uncertainty in the values of log L computed from ϕ_{31}^* and P_1.

3.2. *The Nonradial Pulsation of RRc Stars*

Three of the RR*c* variables presented in Figure 4, namely, V9, V10, and V12, display a modulation of their light curves. On certain occasions the amplitudes of these light curves change on the timescale of days. This is shown in Figure 8, where we present average light curves with selected light curves from individual nights. Such behavior is not typical for stars exhibiting the Blazhko effect (Blazhko 1907; see also the discussion in Smith 1995). In particular, in a sample of 46 stars for which Blazhko periods have been determined, the shortest period is 10.9 days. We find no statistically significant periods for V9, V10, and V12 in the range 5 to 60 days.

This behavior is common in bimodal pulsators (RR Lyrae type RR*d*). To clarify the nature of this modulation we performed a period analysis of the light curves. Power spectra, CLEAN (Roberts, Lehar, & Drehar 1987), and multiharmonic periodograms of raw light curves reveal no radial periods other than those listed in Table 1 and their harmonics and aliases at one cycle/day. However, the periods of all three stars are very close to one-third of a day so that the same portions of the light curves are observed over several weeks. In order to judge the magnitude of any effects of aliasing, we simulated V-band observations of a bimodal pulsating star with P_1 from Table 1 and overtone-to-fundamental period ratio $P_1/P_0 = 0.745$, typical for RR*d* variables (Smith 1995), using the formula

$$V(t) = 0.05 \sin(2\pi t/P_0) + 0.22 \sin(2\pi t/P_1) + n(t) ,$$

where $n(t)$ denotes a Gaussian noise component with standard deviation 0.025 mag. Synthetic light curves were constructed for each of V9, V10, and V12, with the sampling corresponding to the times of real observations. The amplitudes were selected to closely mimic the light curves

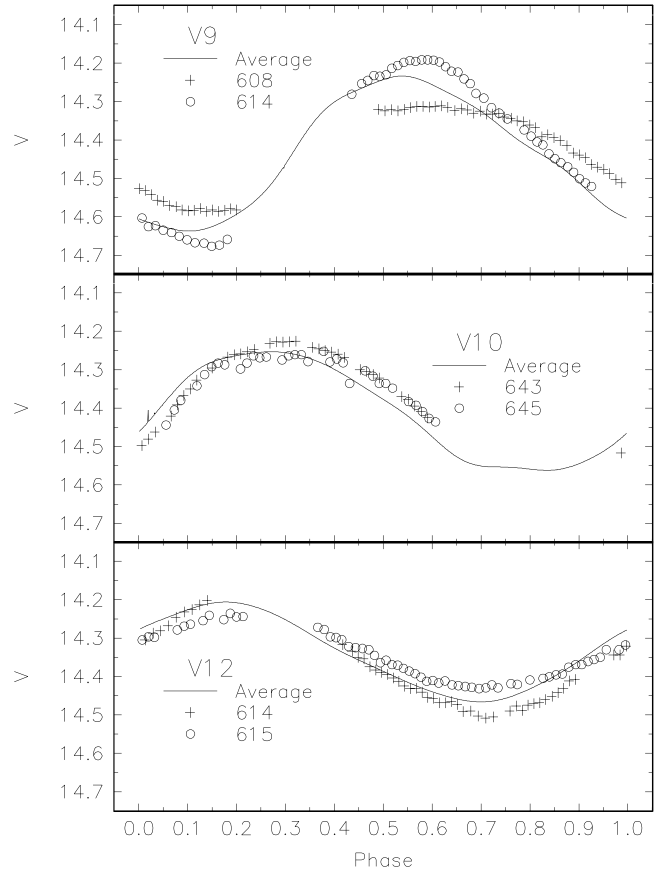

FIG. 8.—Irregular light curves of three RR*c* stars. Light curves for individual nights are labeled with truncated HJD numbers.

observed in Figure 4. The fundamental period P_0 was not detected in power spectra of any of the simulated light curves. Next we prewhitened our real and synthetic light curves by removing a sinusoid with the main period. In all of the power spectra of the prewhitened synthetic light curves, the fundamental period and its aliases were prominent. No periods close to P_0 were detected in any of the prewhitened observed light curves, excluding the possibility of double-mode radial pulsations in these three variables.

Figure 9 (*top*) shows the power spectrum of the observations of variable V9 generated with CLEAN software (Roberts et al. 1987). The most prominent peak is the radial frequency with period $P_1 = 0.316307$ days. The arrow marks the position of the fundamental period, assuming $P_1/P_0 = 0.745$. A second, smaller peak is apparent in the vicinity of the larger peak. To check on the reality of this secondary peak we prewhitened our observed light curves removing a sinusoid with the main period and its two harmonics. The power spectrum of the prewhitened light curve of V9 is presented in Figure 9 (*middle*). The highest peak now corresponds to the frequency of the secondary peak in the first panel, with a period of 0.325128 days. The prewhitened observed light curve, phased with this period, is presented in Figure 9 (*bottom*). The amplitude of this prewhitened light curve is comparable with the amplitude of the scatter in the original light curve of the star.

We performed a similar analysis for variables V10 and V12. In the power spectrum of V10 we again found two very close peaks (Fig. 10, *top*). After prewhitening of the observations, the highest peak in the power spectrum corresponds to a period of 0.330363 days (Fig. 10, *middle*). Figure 10 (*bottom*) shows the observations phased with this period. Variable V12 also shows multiperiodic behavior (Fig. 11, *top*). After prewhitening of the observations the most dominant period is 0.357818 days (Fig. 11, *middle*). Figure 11 (*bottom*) shows the observations phased with this period.

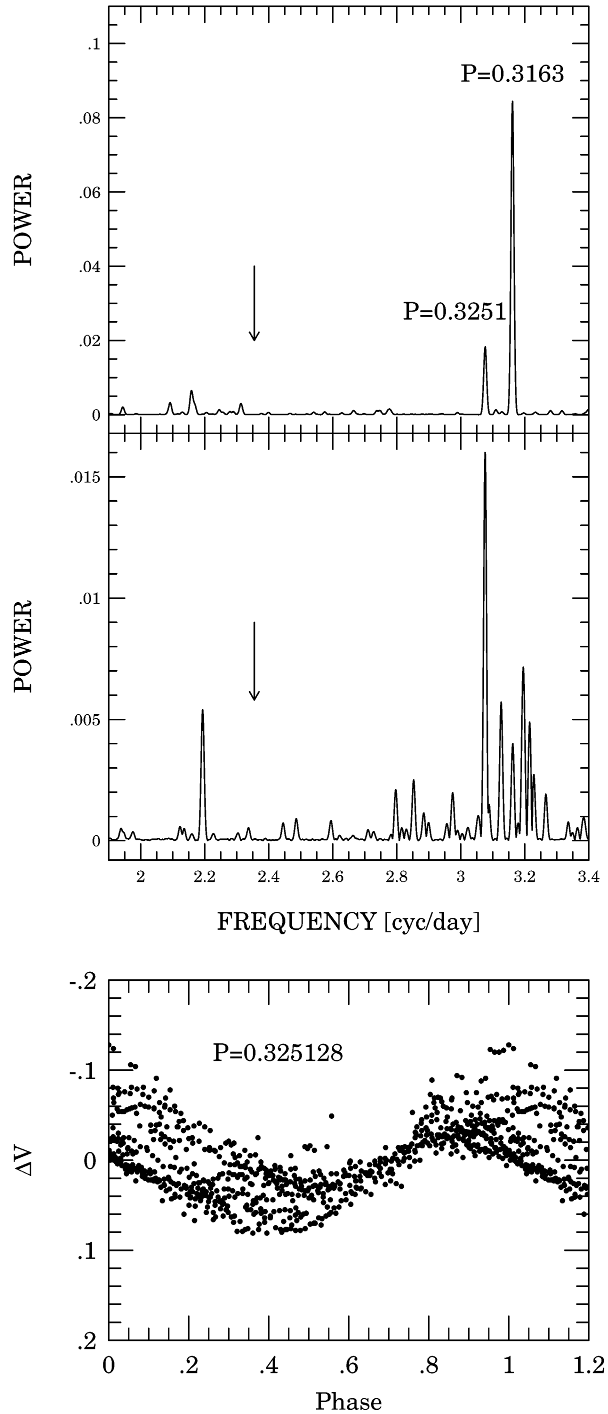

FIG. 9.—Power spectra of the real (*top*) and prewhitened (*middle*) light curve of V9. The arrow marks the suspected position of the fundamental period. The bottom panel shows the light curve of the star phased with the period corresponding to the highest peak in the middle panel.

Although the two main frequencies and the two harmonics of these together contribute about 97% of the power in the light curves of V9, V10, and V12, there are indications

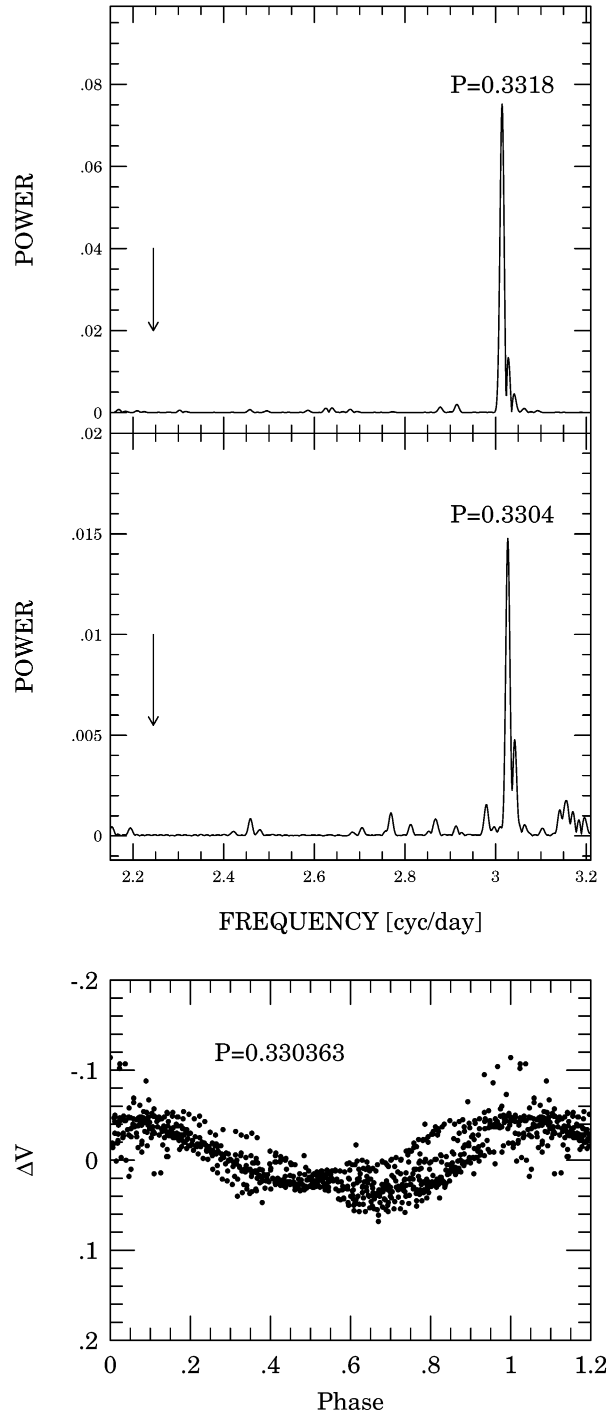

FIG. 10.—Same as in Fig. 9, but for V10

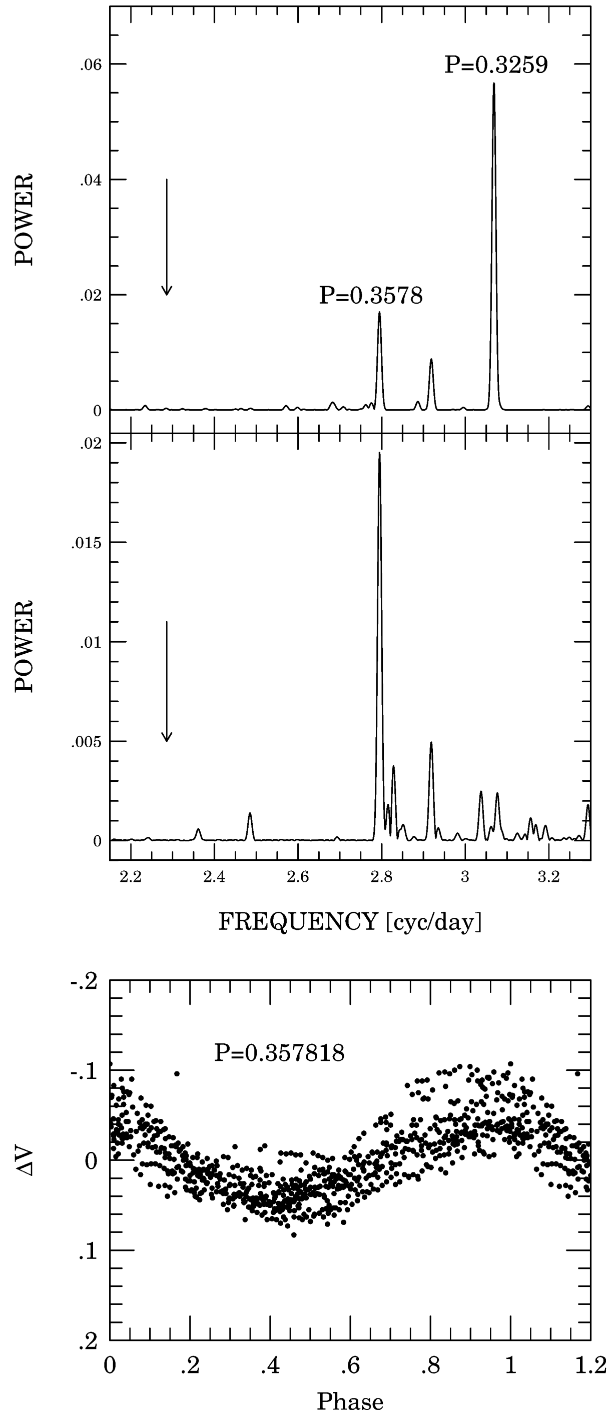

FIG. 11.—Same as in Fig. 9, but for V12

that still more components are present. First, the residual signal has standard deviations of the order of 0.02 mag, at least twice as much as observational errors for these three stars. Second, further prewhitening yields a statistically significant reduction of the variance, according to an F-test. An analysis of the full frequency spectra of these interesting stars is complex, and we postpone it to a later discussion.

Nonradial oscillations with many frequencies are common in δ Scuti variables (main-sequence stars in the instability strip) but have not yet been observed in RR Lyrae stars. The theoretical calculations performed by Van Hoolst et al. (1998) clearly show that low-degree nonradial modes can be excited in RR Lyrae stars. In their model, a large number of unstable low-degree ($l = 1, 2$) modes in the vicinity of the radial modes are partially trapped and therefore have the largest growth rate and as a result are presumably most likely to be excited (see their Fig. 1). We propose that this is exactly what we observe for variables V9, V10, and V12 in M55.

The δ Scuti stars have periods about 10 times shorter than RR Lyrae stars. Data sets consisting of observations over a few consecutive nights cover many tens of cycles of variability with good phase coverage, with the result that the complex period structure can be well determined.

Observations of RR Lyrae light curves are usually not so extensive, with a typical light curve containing 100–200 measurements. Our data are significantly more detailed in both phase coverage and number of observations, with the light curves of our variables V9, V10, and V12 containing over 700 points collected during four months. We conclude that other RR Lyrae variables may also pulsate with nonradial modes but that one needs excellent photometric coverage in order to detect these nonradial frequencies.

3.3. *RRab Variables*

Recently Jurcsik & Kovacs (1996), Kovacs & Jurcsik (1996), Kovacs & Jurcsik (1997), and Jurcsik (1998) have extended the work of Simon & Clement and Simon & Teays, developing methods for obtaining the metallicity, absolute magnitudes, intrinsic colors, and temperatures of RR*ab* stars, based on a Fourier decomposition of V-band light curves. Their formulae are

$$[Fe/H] = -5.038 - 5.394P_0 + 1.345\phi_{31} , \quad (6)$$

$$M_V = 1.221 - 1.396P_0 - 0.477A_1 + 0.103\phi_{31} , \quad (7)$$

$$V_0 - K_0 = 1.585 + 1.257P_0 - 0.273A_1 - 0.234\phi_{31} + 0.062\phi_{41} , \quad (8)$$

$$\log T_{eff} = 3.9291 - 0.1112(V_0 - K_0) - 0.0032[Fe/H] , \quad (9)$$

where $\phi_{41} = \phi_4 - 4\phi_1$ (cf. eq. [1]).

Equations (6)–(9) are valid only for RR*ab* stars with regular light curves, that is, variables with a deviation parameter D_m smaller than 3 (see Jurcsik & Kovacs 1996). In our sample, only variable V1 satisfies this condition. In order to increase the sample size, we include RR*ab* variables with $D_m < 5.5$, a condition satisfied by all of the RR*ab* stars in Table 1 belonging to M55. The results are listed in Table 3, which contains values and errors of A_0, A_1, ϕ_{31}, ϕ_{41}, M_V, [Fe/H], T_{eff}, and D_m. The errors of A_0, A_1, ϕ_{31}, and ϕ_{41} come from the least-squares fitting (cf. eq. [1]), and the errors of M_V and [Fe/H] are computed from formulae given by Jurcsik & Kovacs (1996) and Kovacs & Jurcsik (1996).

In Figure 12, we plot $\langle V \rangle - M_V$ versus $\langle V \rangle$, where $\langle V \rangle$ is the mean V magnitude for the variables. The horizontal line is a fit to the data, giving an apparent distance modulus of 13.65 ± 0.11, comparable to the value of 13.76 listed by Harris (1996) and slightly lower than 13.90 ± 0.09 given by Mandushev et al. (1996) and 13.91 ± 0.08 obtained in this work during the analysis of RR*c* variables. The ~0.2 mag difference in M_V values between the RR*c* stars and the RR*ab* arises from the Baade-Wesselink luminosities, which were used to calibrate the zero point of equation (7), as mentioned in § 3.1 (see also Kovacs & Jurcsik for a discussion).

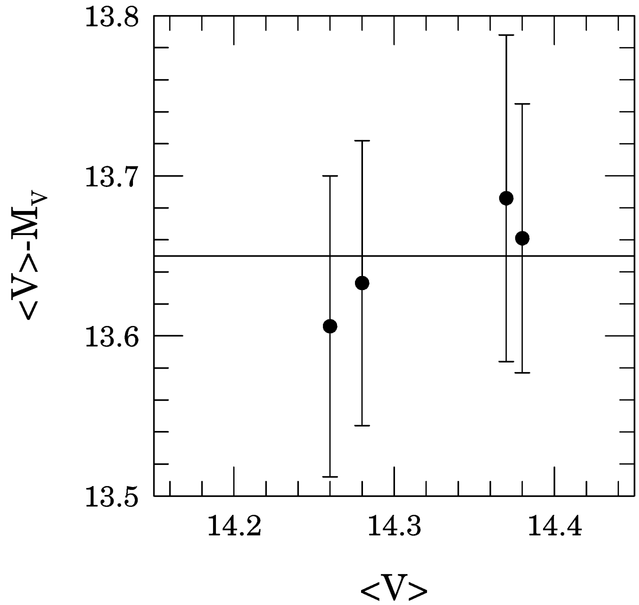

FIG. 12.—$\langle V \rangle - M_V$ vs. $\langle V \rangle$ diagram for the M55 RR*ab* variables. The horizontal line is a fit to the data, giving an apparent distance modulus of 13.65 ± 0.11.

As discussed in § 3.1, previous determinations of the metallicity of M55 vary between −1.54 and −1.96. The Fourier analysis of the RR*ab* stars is consistent with this range, with only variable V8 indicating a larger value of [Fe/H]. However, this star has the largest value of D_m in the present sample of M55 RR*ab* stars. Note also that Kovacs & Jurcsik's metallicity scale is based on Jurcsik's (1995) scale, which differs from that of Zinn & West (1984). Our determinations of [Fe/H] based on the Fourier decomposition of the light curves of RR*ab* variables are consistent with the period-amplitude diagram presented in Figure 6.

The reddening of RR*ab* stars can be calculated from the metallicity, expressed in terms of ΔS (Preston 1959). From

TABLE 3

PARAMETERS FOR THE RR*ab* VARIABLES IN M55

Star	P (days)	A_0	A_1	ϕ_{31}	ϕ_{41}	M_V	[Fe/H]	T_{eff}	D_m
V1	0.579978	14.447	0.438	4.967	1.272	0.719	−1.486	6461	2.62
		±0.000	±0.001	±0.005	±0.007	±0.084	±0.022		
V3	0.661987	14.316	0.358	5.013	1.494	0.647	−1.867	6270	4.72
		±0.000	±0.001	±0.012	±0.022	±0.089	±0.032		
V7	0.682573	14.304	0.346	5.301	2.017	0.654	−1.590	6267	4.44
		±0.001	±0.001	±0.008	±0.013	±0.094	±0.034		
V8	0.721961	14.383	0.248	5.663	2.271	0.684	−1.316	6243	5.12
		±0.001	±0.001	±0.016	±0.038	±0.102	±0.047		
V14	0.521616	18.014	0.353	4.996	1.457	0.844	−1.132	6520	1.40
		±0.001	±0.001	±0.011	±0.017	±0.085	±0.024		
V15	0.637286	18.341	0.164	5.457	2.602	0.821	−1.135	6258	18.46
		±0.001	±0.001	±0.045	±0.093	±0.097	±0.067		

Blanco (1992) we have the relation

$$E(B-V) = \langle B-V \rangle_{\Phi(0.5-0.8)} + 0.01222\Delta S - 0.00045(\Delta S)^2 - 0.185P_0 - 0.356 \quad (10)$$

where $\langle B-V \rangle_{\Phi(0.5-0.8)}$ is the observed mean color in the 0.5–0.8 phase interval. Based on the globular cluster metallicity scale adopted by Zinn & West (1984) and Zinn (1985), Suntzeff et al. (1991) derived the following ΔS-[Fe/H] relation:

$$[\mathrm{Fe/H}] = -0.408 - 0.158\,\Delta S\,. \quad (11)$$

Using equation (11) and adopting a metallicity for M55 of [Fe/H] $= -1.82$ (Zinn & West 1984) we obtain $\Delta S = 8.94$.

The average value of $E(B-V)$ calculated in this way for our four M55 RR*ab* stars is $E(B-V) = 0.11 \pm 0.03$. The reddening in Blanco's analysis is fairly independent of the metallicity over the quoted range. Using a metallicity of [Fe/H] $= -1.54$ (Smith 1984) we derive $E(B-V) = 0.10 \pm 0.03$. A similar calculation for the reddening of the RR*ab* star in Sagittarius with a well-defined light curve (V14 with $D_m = 1.40$) gives $E(B-V) = 0.09$, accepting the value of [Fe/H] determined from the Fourier analysis for this star.

These values are slightly larger than the older determinations of between 0.06 and 0.08 mag (Lee 1977; Reed, Hesser, & Shawl 1988) but are consistent with recent estimates of Buonanno, Corsi, & Fusi Pecci (1989) who obtained $E(B-V) = 0.14 \pm 0.02$ and Peterson (1993) who obtained $E(B-V) = 0.11$. Schlegel, Finkbeiner, & Davis (1998) recently published a new all-sky reddening map based on the *COBE*/DIRBE and *IRAS*/ISSA maps. Their value of $E(B-V)$ at the position of M55 is $E(B-V) = 0.135$ mag, consistent with our estimate.

Adopting a value of $E(B-V) = 0.11 \pm 0.03$ we estimate the absolute distance modulus of M55 to be $(m-M)_0 = 13.31 \pm 0.11$.

3.4. *The Instability Strip*

The red and blue edges of the RR Lyrae zone on the horizontal branch compiled by Smith (1995) vary in $(B-V)_0$ color between 0.155 and 0.19 mag for the blue edge and between 0.38 and 0.44 mag for the red edge. This corresponds to ranges in effective temperature of 7600–7400 K and 6250–6100 K, respectively. In our case the instability strip lies between $B-V = 0.31$ and $B-V = 0.49$ mag. Using a color excess of $E(B-V) = 0.11$ mag, we obtain $(B-V)_0^{\mathrm{BE}} = 0.20$ and $(B-V)_0^{\mathrm{RE}} = 0.38$ mag for the edges of the instability strip, consistent within the errors with estimates made for other globular clusters (Smith 1995).

4. CONCLUSIONS

We have identified nine new RR Lyrae variables in the field of the globular cluster M55. Two of these variables are probable members of the Sagittarius dwarf galaxy. The number of known RR Lyrae variables in M55 is now 13, four RR*ab* stars, and nine RR*c* stars. The periods of the variables indicate that M55 is an Oosterhoff type II cluster.

Three of our nine RR*c* variables exhibit marked amplitude modulation on a timescale of less than a week. We excluded the hypothesis that such behavior is caused by the Blazhko effect or by double-mode radial pulsations. A detailed analysis of the power spectra showed other significant frequencies in the vicinity of the main peak. These frequencies are too close to the main period to be radial pulsations. We conclude that we have detected nonradial pulsation in these RR*c* stars.

We used Fourier decomposition of the V-band light curves of the RR Lyrae variables to estimate luminosities, effective temperatures, metallicities, and masses of these variables. We measure a mean mass of the RR*c* stars in M55 equal to $M = 0.53 \pm 0.03\, M_\odot$, a mean $\log L = 1.75 \pm 0.01$, and a mean effective temperature $T_{\mathrm{eff}} = 7193 \pm 27$ K. The helium abundance that we derive is $Y = 0.27 \pm 0.01$. The blue edge of the instability strip lays at $(B-V)_0 \approx 0.20$ mag, and the red edge at $(B-V)_0 \approx 0.38$ mag. The mean mass of the RR*c* variables is much smaller than expected for a cluster of the metallicity and HB morphology of M55, while the other measured quantities are consistent with those for the sequences of clusters discussed by Simon & Clement (1993) and Kaluzny et al. (1998).

The values of [Fe/H] estimated from the Fourier decomposition of the light curves of the RR*c* stars and the period-amplitude measurements presented in Figure 6 both indicate a metallicity of roughly -1.8 for M55, consistent with the measurements of Suntzeff et al. (1991), McWilliam, Geisler, & Rich (1992), and Minniti et al. (1993), among others.

A similar analysis for the RR*ab* stars suggests a metallicity of roughly -1.5 on the Jurcsik (1995) scale, that is, roughly -1.7 on the Zinn & West (1984) scale. This value is based only on one star with a deviation parameter D_m smaller than 3.0, and as a result is likely to be of low accuracy.

Using the Blanco (1992) dependence of the color excess $E(B-V)$ upon the mean color at minimum light of RR*ab* stars, the pulsation period of the star, and spectroscopic parameter ΔS, we obtained a color excess for M55 of $E(B-V) = 0.11 \pm 0.03$ for an adopted metallicity of [Fe/H] $= -1.8$. We also estimated the values of the visual apparent distance modulus to be equal to 13.65 ± 0.11 from analysis of RR*ab* stars and 13.91 ± 0.08 from analysis of RR*c* variables.

We identified two RR*ab* variables in the M55 field that are probable members of the Sagittarius dwarf galaxy. From the Fourier analysis of their light curves we obtained a metallicity of [Fe/H] $= -1.13$ for both stars. This result is consistent with earlier determinations of metallicity for RR Lyrae variables in the Sagittarius dwarf (Sarajednini & Layden 1995; Mateo et al. 1995; Marconi et al. 1998).

The data used to construct the light curves presented in Figures 3, 4, and 5 are available upon request from the authors.[6]

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[6] See also http://www.astrouw.edu.pl/jka/personal.html.

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