THE ASTRONOMICAL JOURNAL, 121:1533–1550, 2001 March

IMAGE-SUBTRACTION PHOTOMETRY OF VARIABLE STARS IN THE FIELD OF THE GLOBULAR CLUSTER NGC 6934[1]

J. KALUZNY,[2] A. OLECH,[3] AND K. Z. STANEK[4,5]
Received 2000 October 16; accepted 2000 December 5

ABSTRACT

We present CCD *BVI* photometry of 85 variable stars from the field of the globular cluster NGC 6934. The photometry was obtained with the image subtraction package ISIS. 35 variables are new identifications: 24 RRab stars, five RRc stars, two eclipsing binaries of W UMa-type, one SX Phe star, and three variables of other types. Both detected contact binaries are foreground stars. The SX Phe variable belongs most likely to the group of cluster blue stragglers. Large number of newly found RR Lyr variables in this cluster, as well as in other clusters recently observed by us, indicates that total RR Lyr population identified up to date in nearby galactic globular clusters is significantly (>30%) incomplete. Fourier decomposition of the light curves of RR Lyr variables was used to estimate the basic properties of these stars. From the analysis of RRc variables we obtain a mean mass of $M = 0.63\ M_\odot$, luminosity $\log L/L_\odot = 1.72$, effective temperature $T_{\rm eff} = 7300$ and helium abundance $Y = 0.27$. The mean values of the absolute magnitude, metallicity (on Zinn's scale) and effective temperature for RRab variables are $M_V = 0.81$, [Fe/H] $= -1.53$ and $T_{\rm eff} = 6450$, respectively. From the $B-V$ color at minimum light of the RRab variables we obtained the color excess to NGC 6934 equal to $E(B-V) = 0.09 \pm 0.01$. Different calibrations of absolute magnitudes of RRab and RRc available in literature were used to estimate apparent distance modulus of the cluster: $(m - M)_V = 16.09 \pm 0.06$. We note a likely error in the zero point of the *HST*-based *V*-band photometry of NGC 6934 recently presented by Piotto et al. Among analyzed sample of RR Lyr stars we have detected a short period and low amplitude variable which possibly belongs to the group of second overtone pulsators (RRe subtype variables). The *BVI* photometry of all variables is available electronically via anonymous ftp. The complete set of the CCD frames is available upon request.

Key words: color-magnitude diagrams — globular clusters: individual (NGC 6934) — methods: data analysis — stars: oscillations — stars: variables: other

1. INTRODUCTION

NGC 6934 (R.A. = $20^{\rm h}34^{\rm m}$, Decl. = $+7°24'$, J2000.0) is an intermediate-metallicity globular cluster. In his catalog Harris (1996) adopted for it [Fe/H] = -1.54. The color magnitude diagrams of this cluster were obtained by Harris & Racine (1973), Brocato et al. (1998) and Piotto et al. (1999). The cluster was extensively searched for variable stars by Sawyer-Hogg & Wehlau (1980), who listed 51 variable stars, 50 of which were RR Lyr variables. They have found mean periods for 45 RRab and five RRc stars equal to 0.552 days and 0.294 days, respectively. These values place NGC 6934 among Oosterhoff type I clusters.

2. OBSERVATIONS AND REDUCTIONS

Observations analyzed in this paper were obtained as result of a side-survey conducted during project DIRECT (Kaluzny et al. 1998b; Stanek et al. 1998). The cluster was monitored with the 1.2 m telescope at the F. L. Whipple Observatory (FLWO), where we used "AndyCam" camera (Szentgyorgyi et al. 2001, in preparation) containing Loral 2048^2 backside illuminated CCD. The pixel scale was 0".32 pixel^{-1}, giving field of view roughly 11 × 11 arcmin^2. The monitored field covers most of the cluster area as the tidal radius of NGC 6934 is estimated at $r = 8'.37$ (Harris 1996). The data were collected from 1997 July 15 to September 23. The cluster was observed early in the night when main targets of the DIRECT project, M31 and M33, were located too far east to observe. Photometry of variable stars presented in this paper is based on 78 *V*-band images, 22 *B*-band images and 21 *I*-band images, collected during 15 nights.[6] For almost all *V*-band images an exposure time was set to 450 s and the median value of seeing for that filter was FWHM = 1".7. Preliminary processing of the CCD frames was done with the standard routines in the IRAF CCDPROC package.[7]

Initially, we reduced our data by extracting profile photometry with the DAOPHOT/ALLSTAR package (Stetson 1987, 1991). We followed a procedure adopted by the DIRECT team, which is described in detail in Kaluzny et al. (1998b). Inspection of derived databases lead to recovery of 50 out of 51 variables listed in Sawyer-Hogg & Wehlau (1980). The only unrecovered variable, star V15, was missed due to fact that its images were overexposed on most of

[1] Based on observations obtained with the 1.2 m Telescope at the F. L. Whipple Observatory of the Harvard-Smithsonian Center for Astrophysics.

[2] Copernicus Astronomical Center, ul. Bartycka 18, 00-716 Warsaw, Poland; jka@camk.edu.pl.

[3] Warsaw University Observatory, Al. Ujazdowskie 4, 00-478 Warsaw, Poland; olech@sirius.astrouw.edu.pl.

[4] Hubble Fellow.

[5] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, MS20, Cambridge, MA 02138; kstanek@cfa.harvard.edu.

[6] The complete list of exposures for the cluster and related data files are available through anonymous ftp at cfa-ftp.harvard.edu, in the directory pub/kstanek/NGC6934. Please retrieve the "README" file for instructions.

[7] IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under agreement with the National Science Foundation.

TABLE 1

BASIC ELEMENTS OF VARIABLES FROM THE FIELD OF NGC 6934

Star	$\alpha_{J2000.0}$	$\delta_{J2000.0}$	P (days)	HJD_{max} 2450000+	A_V	$\langle B \rangle$	$\langle V \rangle$	$\langle I \rangle$	Type
V1	20 34 08.4	7 23 39	0.56751*	...	0.60	17.34	16.92	16.22	RRab
V2	20 34 08.6	7 24 02	0.481947	637.595 ± 0.010	1.03	17.29	16.90	16.35	RRab
V3	20 34 11.4	7 25 15	0.539806	674.894 ± 0.011	1.09	17.22	16.85	16.28	RRab
V4	20 34 13.9	7 25 15	0.616422	681.370 ± 0.015	1.10	17.27	16.69	16.21	RRab
V5	20 34 15.2	7 27 58	0.564560	...	0.81	17.49	17.01	16.31	RRab
V6	20 34 09.5	7 23 45	0.555866	639.704 ± 0.012	1.03	17.47	16.96	16.44	RRab
V7	20 34 17.4	7 25 16	0.644049	683.624 ± 0.013	0.68	17.29	16.82	16.19	RRab
V8	20 34 18.0	7 25 08	0.623984	...	0.60	17.43	16.95	16.22	RRab
V9	20 34 15.6	7 24 36	0.549156	674.914 ± 0.010	0.97	17.34	16.89	16.29	RRab
V10	20 34 02.2	7 25 28	0.519959	595.465 ± 0.010	1.30	17.42	16.94	16.36	RRab
V11	20 34 12.5	7 24 46	0.30867*	677.784 ± 0.007	0.50	17.13	16.88	16.40	RRc
V12	20 34 13.2	7 23 34	0.464215	681.024 ± 0.009	1.11	...	16.95	16.44	RRab
V13	20 34 08.1	7 24 42	0.551334	682.304 ± 0.011	0.87	17.36	16.94	16.32	RRab
V14	20 34 10.9	7 22 47	0.521990	...	1.00	17.42	16.85	16.32	RRab
V16	20 34 13.7	7 24 36	0.604853	675.344 ± 0.012	0.77	17.41	16.90	16.22	RRab
V17	20 34 06.5	7 22 30	0.598272	683.774 ± 0.010	0.70	17.40	16.91	16.25	RRab
V18	20 34 14.6	7 24 09	0.956070	680.944 ± 0.019	0.47	16.98	16.50	15.79	RRab
V19	20 34 13.2	7 24 19	0.480550	676.761 ± 0.016	...	...	...	...	RRab
V20	20 34 09.6	7 24 34	0.54833*	682.554 ± 0.011	1.02	17.23	16.78	16.23	RRab
V21	20 34 08.9	7 24 15	0.526829	...	0.69	17.45	16.94	16.40	RRab
V22	20 33 55.3	7 21 24	0.574280	...	0.50	17.47	16.93	16.30	RRab
V23	20 34 09.3	7 24 00	0.28643*	675.303 ± 0.006	...	...	...	...	RRc
V24	20 34 13.8	7 23 24	0.641670	681.944 ± 0.013	0.46	...	16.94	16.29	RRab
V25	20 34 14.7	7 24 54	0.509086	...	1.01	17.36	16.88	16.33	RRab
V26	20 34 13.4	7 21 02	0.259318	677.282 ± 0.009	0.39	17.24	16.96	16.57	RRc
V27	20 34 01.4	7 27 39	0.592204	684.314 ± 0.012	0.84	17.46	16.88	16.21	RRab
V28	20 33 55.6	7 25 56	0.485151	675.483 ± 0.010	1.31	17.33	16.87	16.41	RRab
V29	20 34 05.7	7 21 14	0.454818	...	1.32	17.56	17.08	16.66	RRab
V30	20 34 22.1	7 26 26	0.589853	684.164 ± 0.012	0.79	17.43	16.92	16.25	RRab
V31	20 34 21.1	7 22 37	0.505070	674.910 ± 0.010	1.20	17.41	16.95	16.39	RRab
V32	20 34 10.6	7 25 08	0.511948	682.844 ± 0.009	1.23	17.35	16.84	16.36	RRab
V33	20 34 13.8	7 24 29	0.518445	...	1.32	17.43	16.97	16.33	RRab
V34	20 34 09.9	7 24 32	0.560103	684.424 ± 0.010	0.97	17.32	16.82	16.25	RRab
V35	20 34 21.9	7 21 56	0.544222	681.090 ± 0.020	0.76	17.48	16.99	16.32	RRab
V36	20 34 12.1	7 23 41	0.495659	677.153 ± 0.010	1.19	17.45	16.89	16.32	RRab
V37	20 34 12.9	7 24 28	0.533186	676.433 ± 0.011	1.20	...	16.87	...	RRab
V38	20 34 12.2	7 23 59	0.523562	602.890 ± 0.010	1.04	17.18	16.71	...	RRab
V39	20 34 11.9	7 24 00	0.502578	675.753 ± 0.011	1.06	17.08	16.73	16.28	RRab
V40	20 34 10.7	7 24 44	0.560755	677.924 ± 0.011	0.96	...	16.81	16.22	RRab
V41	20 34 13.3	7 23 38	0.520404	709.710 ± 0.010	1.10	17.40	16.94	16.29	RRab
V42	20 34 15.0	7 24 39	0.524235	641.634 ± 0.010	1.21	17.28	16.95	16.40	RRab
V43	20 34 12.8	7 24 45	0.563218	684.662 ± 0.011	0.92	17.32	16.83	16.25	RRab
V44	20 34 08.5	7 23 48	0.630384	676.224 ± 0.013	0.50	17.39	16.90	16.22	RRab
V45	20 34 09.2	7 24 08	0.53660*	...	1.35	...	16.97	16.35	RRab
V46	20 34 12.3	7 23 53	0.328557	676.104 ± 0.010	0.41	17.03	16.76	16.33	RRc
V47	20 34 12.0	7 23 52	0.640938	677.943 ± 0.013	0.48	17.23	16.81	16.23	RRab
V48	20 34 13.5	7 25 08	0.561299	675.854 ± 0.011	0.93	17.23	16.88	16.30	RRab
V49	20 34 12.2	7 23 22	0.285460	675.440 ± 0.010	0.50	17.15	16.80	...	RRc
V50	20 34 12.4	7 23 41	0.634510	678.365 ± 0.013	0.47	17.37	16.88	16.24	RRab
V51	20 34 11.8	7 24 52	0.564769	678.143 ± 0.011	0.80	17.20	16.73	...	RRab
NV52......	20 34 18.3	7 22 14	0.05976	681.135 ± 0.002	0.46	19.27	18.92	18.48	SX Phe
NV53......	20 34 13.6	7 24 00	0.28235	683.365 ± 0.007	0.49	17.16	16.88	16.45	RRc
NV54......	20 34 12.6	7 24 35	0.59020	680.304 ± 0.011	0.73	17.27	16.79	16.19	RRab
NV55......	20 34 13.3	7 24 27	0.77828	675.834 ± 0.015	0.25	17.15	16.66	15.98	RRab
NV56......	20 34 12.5	7 24 18	0.29104	675.274 ± 0.007	0.46	17.02	16.64	...	RRc
NV57......	20 34 12.4	7 24 10	0.68712	...	...	...	...	...	RRab
NV58......	20 34 12.1	7 25 05	0.40082	676.995 ± 0.008	0.47	17.04	16.69	16.15	RRc
NV59......	20 34 12.0	7 24 15	0.53855	...	...	...	...	...	RRab
NV60......	20 34 12.0	7 24 56	0.66040	684.102 ± 0.012	0.40	17.31	16.85	16.20	RRab
NV61......	20 34 11.9	7 23 10	0.528?	...	0.38	17.24	16.87	16.29	RRab?
NV62......	20 34 11.7	7 24 26	0.53067	682.394 ± 0.011	...	...	...	...	RRab
NV63......	20 34 11.6	7 24 26	0.57564	675.889 ± 0.012	...	...	...	...	RRab
NV64......	20 34 11.4	7 24 18	0.57102	678.323 ± 0.011	...	...	...	...	RRab
NV65......	20 34 11.4	7 24 15	0.65905	677.144 ± 0.013	...	...	...	...	RRab

TABLE 1—*Continued*

Star	$\alpha_{J2000.0}$	$\delta_{J2000.0}$	P (days)	HJD_{max} 2450000+	A_V	$\langle B \rangle$	$\langle V \rangle$	$\langle I \rangle$	Type
NV66......	20 34 11.1	7 24 16	0.54078	680.944 ± 0.011	...	...	...	...	RRab
NV67......	20 34 10.9	7 23 55	0.61333	675.990 ± 0.012	...	...	...	...	RRab
NV68......	20 34 10.9	7 24 00	0.33534	683.194 ± 0.007	...	...	...	...	RRc
NV69......	20 34 10.8	7 23 15	0.24700	684.223 ± 0.005	0.09	17.17	16.90	16.57	RRe?
NV70......	20 34 10.7	7 24 06	0.53935	680.043 ± 0.013	...	...	...	...	RRab
NV71......	20 34 10.7	7 23 54	0.57269	...	...	...	...	...	RRab
NV72......	20 34 10.5	7 25 20	0.66785	675.814 ± 0.012	0.29	17.29	16.85	16.18	RRab
NV73......	20 34 09.8	7 24 47	0.50621	...	0.51	17.29	16.92	16.42	RRab
NV74......	20 34 09.3	7 24 08	0.56813	...	1.00	17.35	16.86	16.23	RRab
NV75......	20 34 02.8	7 19 35	0.28207	...	0.36	17.78	17.15	16.23	EW
NV76......	20 33 54.6	7 19 50	0.33649	...	0.31	18.23	17.94	17.58	EW
NV77......	20 34 10.5	7 24 24	...	...	19.43	19.10	18.36	...	LP
NV78......	20 34 12.1	7 24 38	0.54230	...	...	...	...	...	RRab
NV79......	20 34 10.5	7 24 24	0.62187	678.584 ± 0.012	...	...	...	...	RRab
NV80......	20 34 11.7	7 24 07	0.54427	676.154 ± 0.011	...	17.25	16.77	...	RRab
NV81......	20 34 11.2	7 24 23	0.57262	676.835 ± 0.013	...	...	...	...	RRab
NV82......	20 34 10.7	7 24 17	0.73113	683.544 ± 0.014	...	...	...	...	RRab
NV83......	20 34 11.2	7 24 26	0.54055	677.906 ± 0.018	...	...	...	...	RRab
NV84......	20 34 12.1	7 24 28	0.66535	682.104 ± 0.013	...	...	...	...	RRab
NV85......	20 34 31.0	7 21 57	1.622	...	0.13	18.34	17.46	16.33	?
NV86......	20 34 19.5	7 22 51	~49	...	0.15	15.53	13.90	12.03	LP

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

frames. In addition we identified 27 new variables located in the cluster field.

We attempted to improve quality of derived light curves by employing image subtraction package ISIS.V2.1 (Alard & Lupton 1998; Alard 2000).[8] It resulted not only in better quality of photometry for already identified variables but also allowed us to find six additional variable objects. We followed prescription given in the ISIS.V2 manual to obtain differential light curves expressed in ADU units. An additional step is needed to convert ISIS light curves into magnitudes. This was accomplished by using DAOPHOT/ALLSTAR-based profile photometry derived from individual images selected as templates (one image for every filter). For every variable its total flux registered on a template image was derived based on its individual magnitude and an appropriate aperture correction for a given frame. For some variables their profile photometry turned out to be unreliable due to problems caused by crowding in the innermost part of the cluster. For these stars we decided to give up on transforming their ISIS-based light curves into magnitude units. Specifically, we transformed to magnitude units only stars for which ALLSTAR returned profile photometry with $\sigma \leq 0.05$ and $CHI1 \leq 3.0$.

Transformation from the instrumental magnitudes to the standard BVI_c system was accomplished based on observations of a few dozen stars from several Landolt (1992) fields. These date were collected on 2 photometric nights. The following relations were adopted for the night of 1997 September 22/23:

$$v = V + 0.038 \times (B-V) + 0.116 \times X + \text{constant} , \quad (1)$$

$$b = B - 0.035 \times (B-V) + 0.198 \times X + \text{constant} , \quad (2)$$

$$i = I - 0.054 \times (V-I) + 0.052 \times X + \text{constant} . \quad (3)$$

We estimate that total uncertainties (including uncertainty of aperture corrections) of the zero points of cluster photometry should not exceed 0.035 mag for all three filters used.

3. RESULTS

In our search for variables in NGC 6934 we have identified 85 stars. 50 of them were previously known (Sawyer Hogg & Wehlau 1980) and 35 are new discoveries. All previously known variables are RR Lyr stars with five objects belonging to Bailey type c and 45 belonging to Bailey type ab. Among newly identified variables we have detected 24 RRab stars, five RRc stars, two eclipsing W UMa-type stars, one SX Phe star and three other objects.

Basic elements (coordinates, periods, A_V amplitudes, intensity averaged BVI magnitudes and types) for all variables from our sample are presented in Table 1.[9] We assigned names NV52–NV84 to the newly identified objects. Transformation from rectangular coordinates returned by DAOPHOT to the equatorial coordinates was obtained based on positions of 40 stars from the USNO-A2 catalog (Monet et al. 1996) identified in our field. For variables V1–V51 we adopted periods from C. M. Clement (1997, private communication). The exception from that rule are variables V1, V11, V20, V23, and V45 for which we obtained revised periods based on our data alone. These new periods produce less scattered light curves than old ones. Periods for the newly identified variables NV52–NV86, as well as for five other objects listed above, were derived using ORT algorithm developed by Schwarzenberg-Czerny (1997).

Finding charts for all variables discussed in this paper are shown in Figure 1. Each chart is 40″ wide with north up and east to the left. In Figure 2 we present V-band light curves for variables whose ISIS-based photometry was trans

[8] ISIS2 package can be downloaded from http://www.iap.fr/users/alard/package.html.

[9] In the presented analysis we are using solely light curves based on ISIS results.

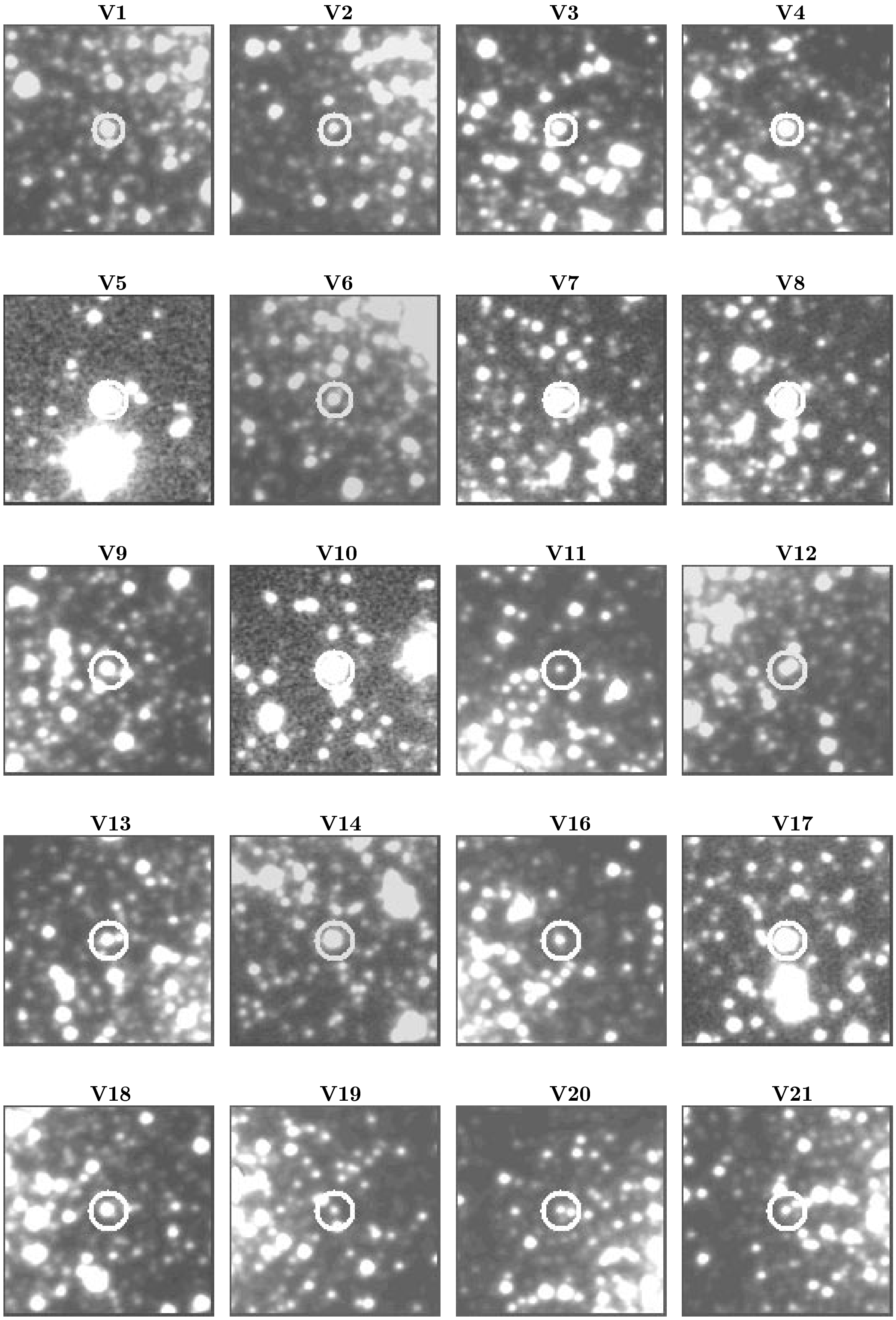

FIG. 1.—Finder charts for NGC 6934 variables. Each chart is 40″ wide with north up and east to the left.

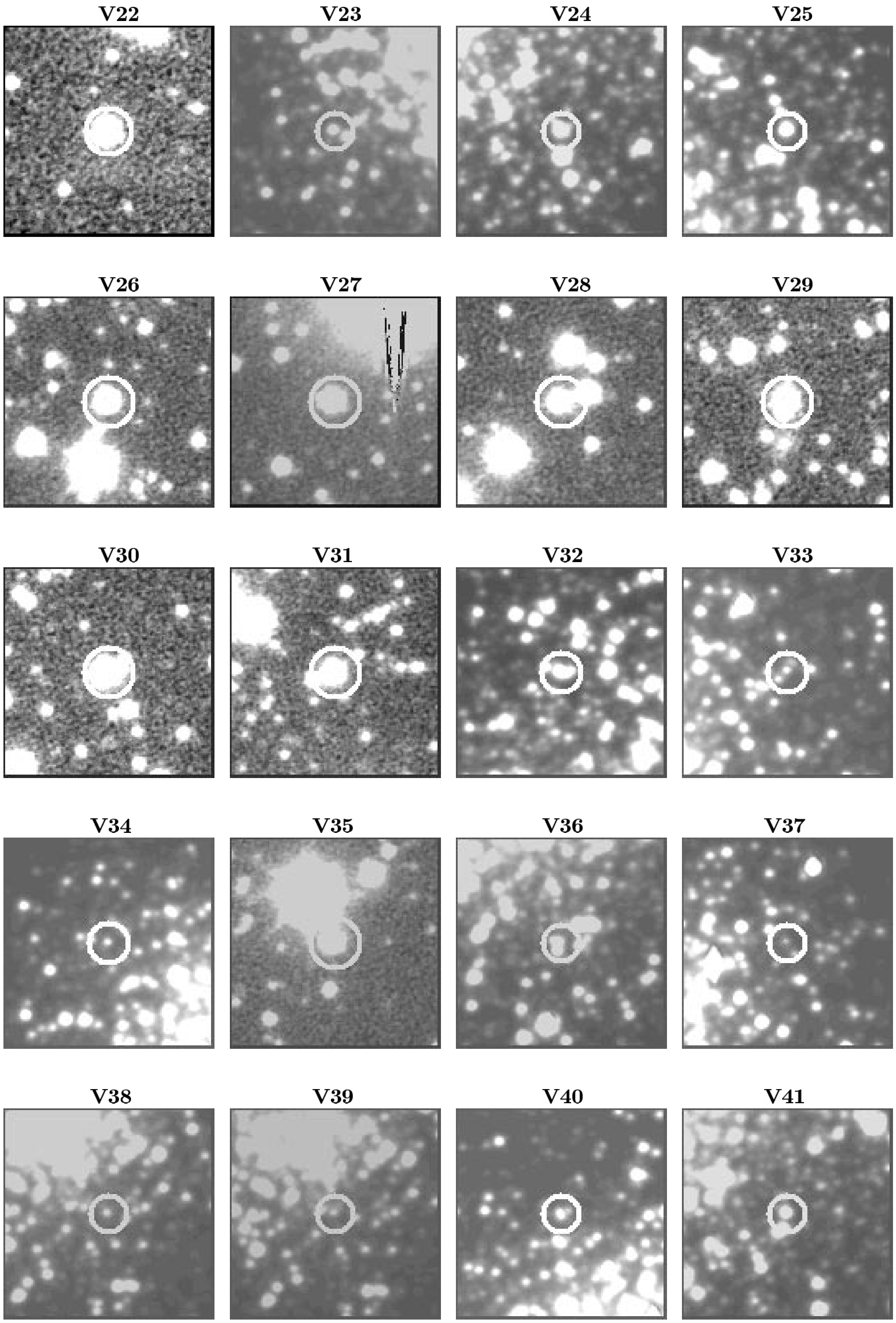

Fig. 1.—*Continued*

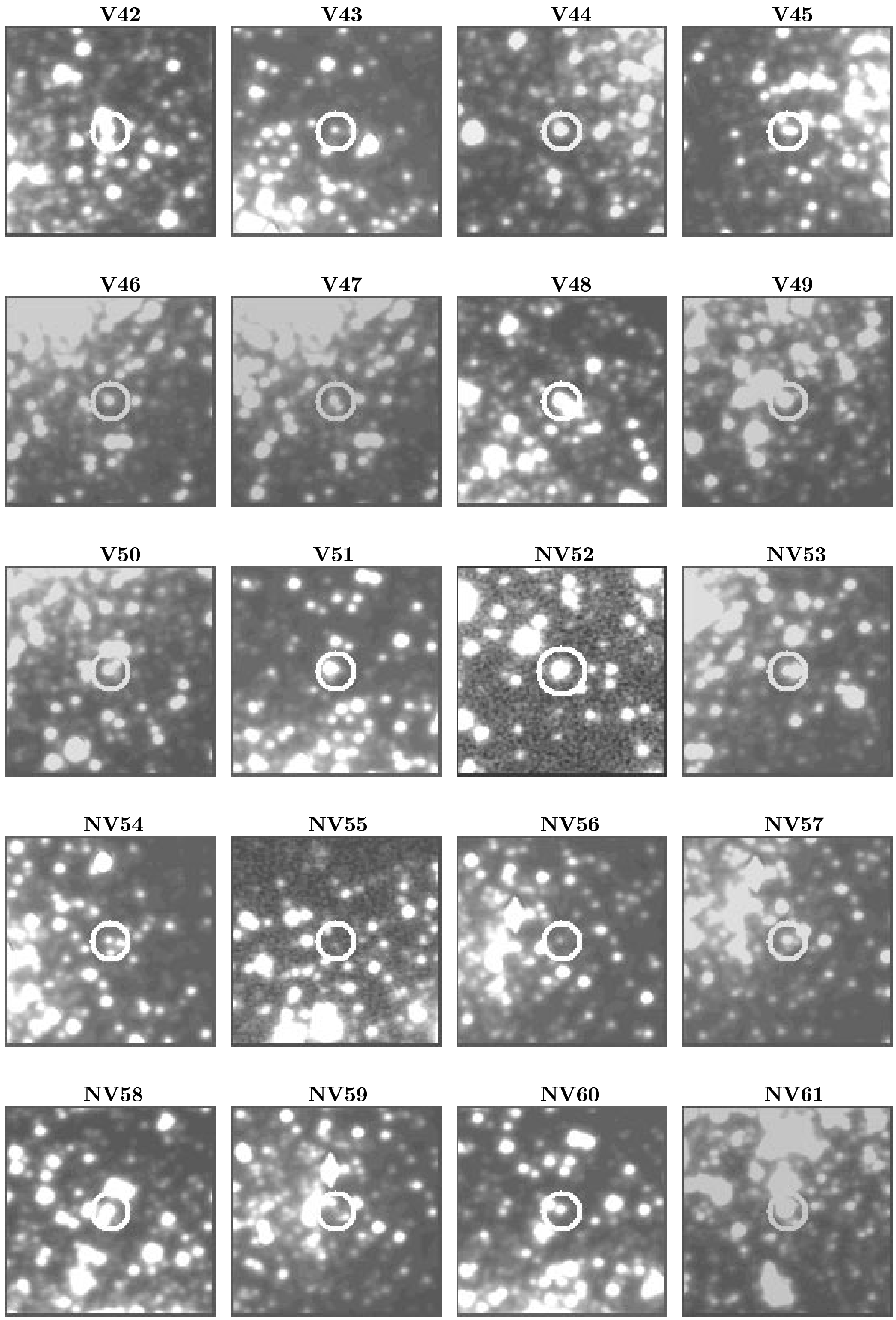

FIG. 1.—*Continued*

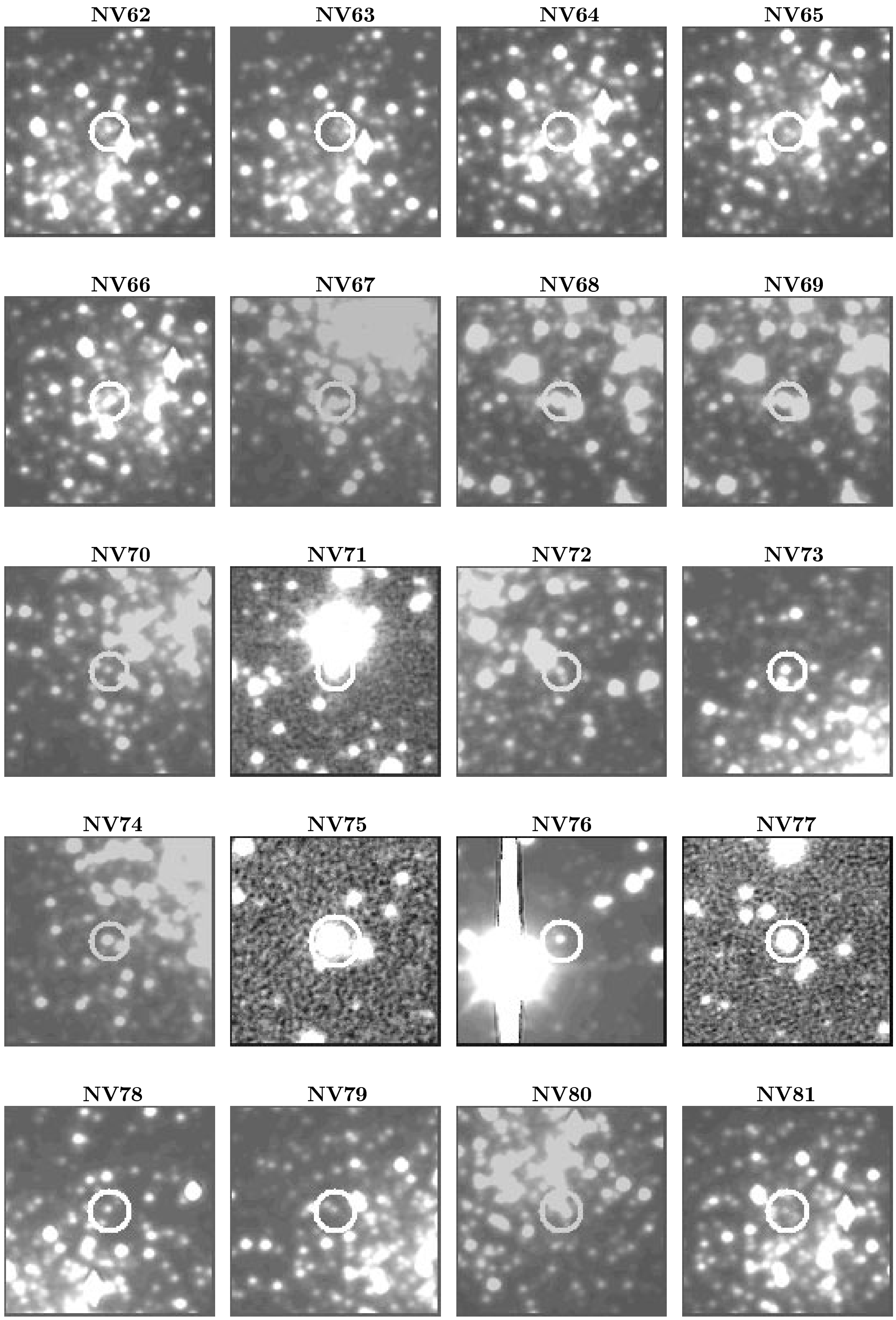

FIG. 1.—*Continued*

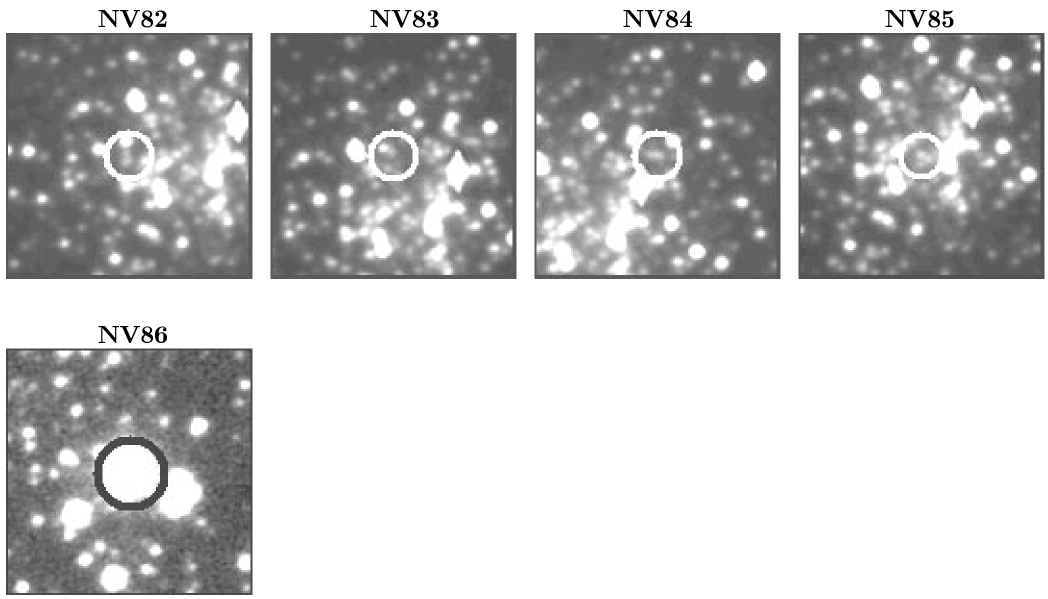

FIG. 1.—*Continued*

formed into magnitude units. Light curves which were left in the differential counts units are shown in Figure 3.

In Figure 4 we show the map of the inner part of NGC 6934 with positions of the variables marked by open circles. The dotted line marks the central part of the cluster with $r = 0.9$ arcmin. In this circle, for clarity, we do not plot the constant stars. Note that we find variable stars all the way to the center of the cluster.

In Figure 5 we present a $V/B-V$ and $V/V-I$ color-magnitude diagrams derived for the field of NGC 6934. For every filter presented photometry was obtained by averaging ALLSTAR results obtained from 5–11 frames. Identified variable stars are marked with special symbols in Figure 5. A section of the $V/B-V$ color-magnitude diagram showing in some detail morphology of the horizontal branch of the cluster is presented in Figure 6.

We note that our survey increased by almost 60% population of known RR Lyr variables in NGC 6934. Similar results were recently reported for other well-studied clusters like M5 (Olech et al. 1999b), M55 (Olech at al. 1999a) or NGC 6362 (Mazur, Kaluzny, & Krzeminski 1999). It seems that contrary to some claims (e.g., Suntzeff, Kinman, & Kraft 1991), the sample of RR Lyr variables identified up to date in galactic globular clusters is significantly incomplete.

3.1. *RR Lyr Variables*

The majority of variable stars identified in NGC 6934 are of RR Lyr type. Among them there are 10 RRc stars and 69 RRab stars. Such a large ratio of RRab to RRc variables is common for Oosterhoff type I globular clusters. According to Smith (1995) the average ratio between the number of RRc stars and all RR Lyr variables $n(c)/n(c+ab)$ in Oosterhoff type I clusters is equal to 0.17 and for Oosterhoff type II clusters it is equal to 0.44. For NGC 6934 we obtained $n(c)/n(c+ab) = 0.13$.

The periods of RRab variables from NGC 6934 are between 0.4548 and 0.956 days with the mean value of 0.574 days. Periods of RRc stars are between 0.247 and 0.4008 days with the mean at 0.310 days. According to Smith (1995) the mean periods of RRc and RRab stars are 0.32 days and 0.55 days in Oosterhoff type I clusters and 0.37 days and 0.64 days in Oosterhoff type II clusters.

The values of amplitudes A_V and periods P presented in Table 1 are used to plot the period-amplitude ($\log P - A_V$) diagram shown in Figure 7. Open circles denote RRc stars, filled triangles RRab stars with $D_m < 3$ (for definition of D_m see Kovacs & Kanbur 1998) and open triangles RRab variables with $D_m > 3$. The solid line represents a linear fit to RRab variables in M3 (Kaluzny et al. 1998a) an another Oosterhoff type I globular cluster. One can see that RRab variables from NGC 6934 follow closely the linear relation for M3. It is not surprising because both clusters have very similar metallicities.

We fitted our V-band light curves with Fourier sine series of the form

$$V = A_0 + \sum_{j=1}^{6} A_j \cdot \sin(j\omega t + \phi_j) , \quad (4)$$

where $\omega = 2\pi/P$. To find the values of ω, A_j and ϕ_j we employed the method developed by Schwarzenberg-Czerny (1997) and Schwarzenberg-Czerny & Kaluzny (1998). The elements of the Fourier decomposition of the light curves are used in the following subsections for determination of the physical parameters for RR Lyr variables from NGC 6934.

3.1.1. *A Fourier Analysis of the RRc Stars*

It was demonstrated by Simon & Clement (1993) that Fourier decomposition of light curves of RRc variables is a very useful technique for determining physical parameters of these stars. The equations of Simon & Clement (1993) are

$$\log M = 0.52 \log P_1 - 0.11\phi^*_{31} + 0.39 , \quad (5)$$

$$\log L = 1.04 \log P_1 - 0.058\phi^*_{31} + 2.41 , \quad (6)$$

$$\log T_{\rm eff} = 3.265 - 0.3026 \log P_1 - 0.1777 \log M + 0.2402 \log L , \quad (7)$$

$$\log Y = -20.26 + 4.935 \log T_{\rm eff} - 0.2638 \log M + 0.3318 \log L , \quad (8)$$

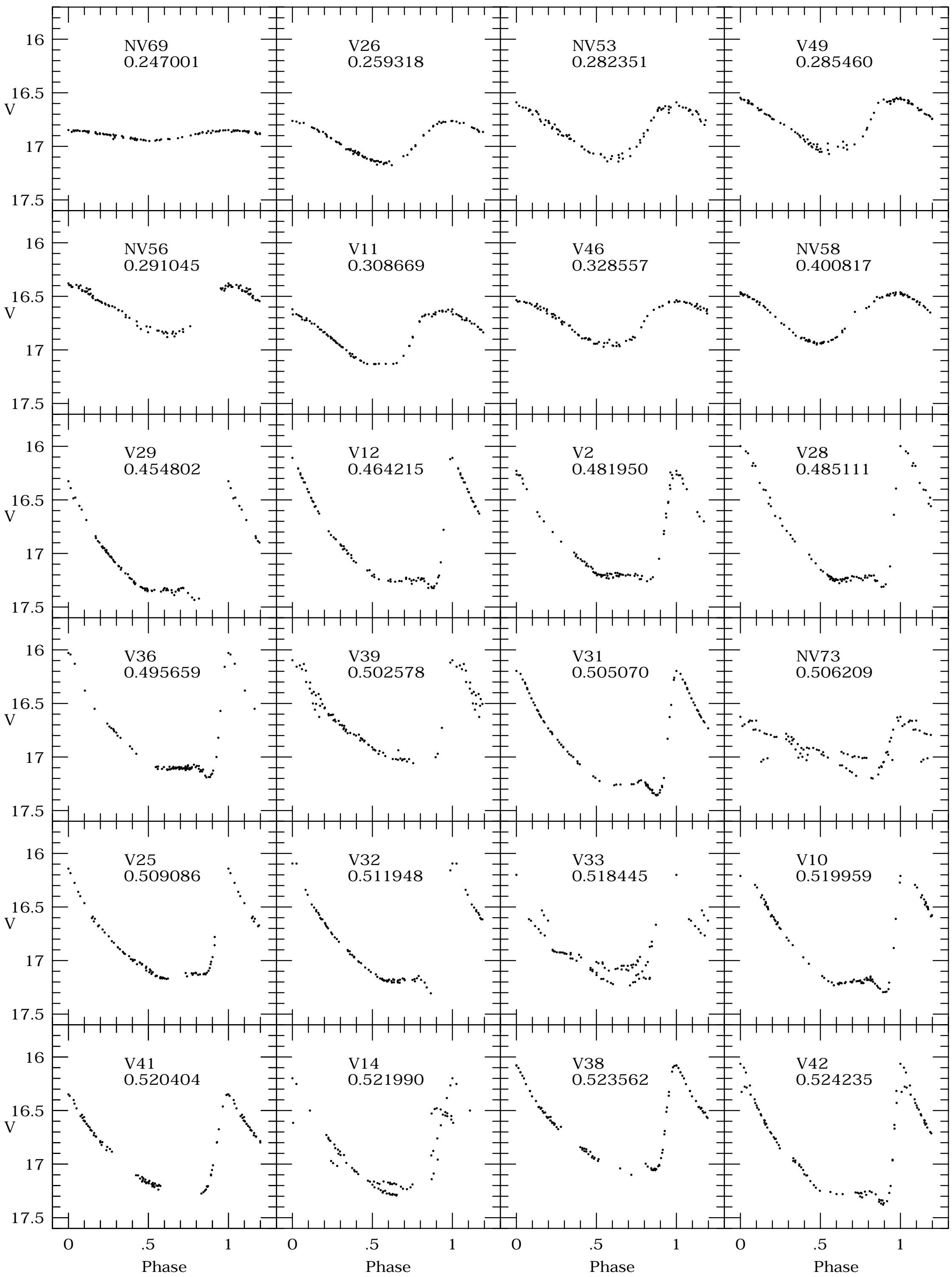

FIG. 2.—V-band light curves of variables for which ISIS photometry was transformed to magnitudes. The stars are plotted according to the increasing period.

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, $T_{\rm eff}$ is the effective temperature, Y is the relative helium abundance, and $\phi^*_{31} = \phi^*_3 - 3\phi^*_1$. The phases marked by 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. [4]). For ϕ_{31} we have $\phi_{31} = \phi^*_{31} + \pi$.

From equations (5)–(8) we computed masses, luminosities, effective temperatures, relative helium abundances and absolute magnitudes of RRc stars in NGC 6934. These are presented in Table 2 together with the values of A_0, A_1,

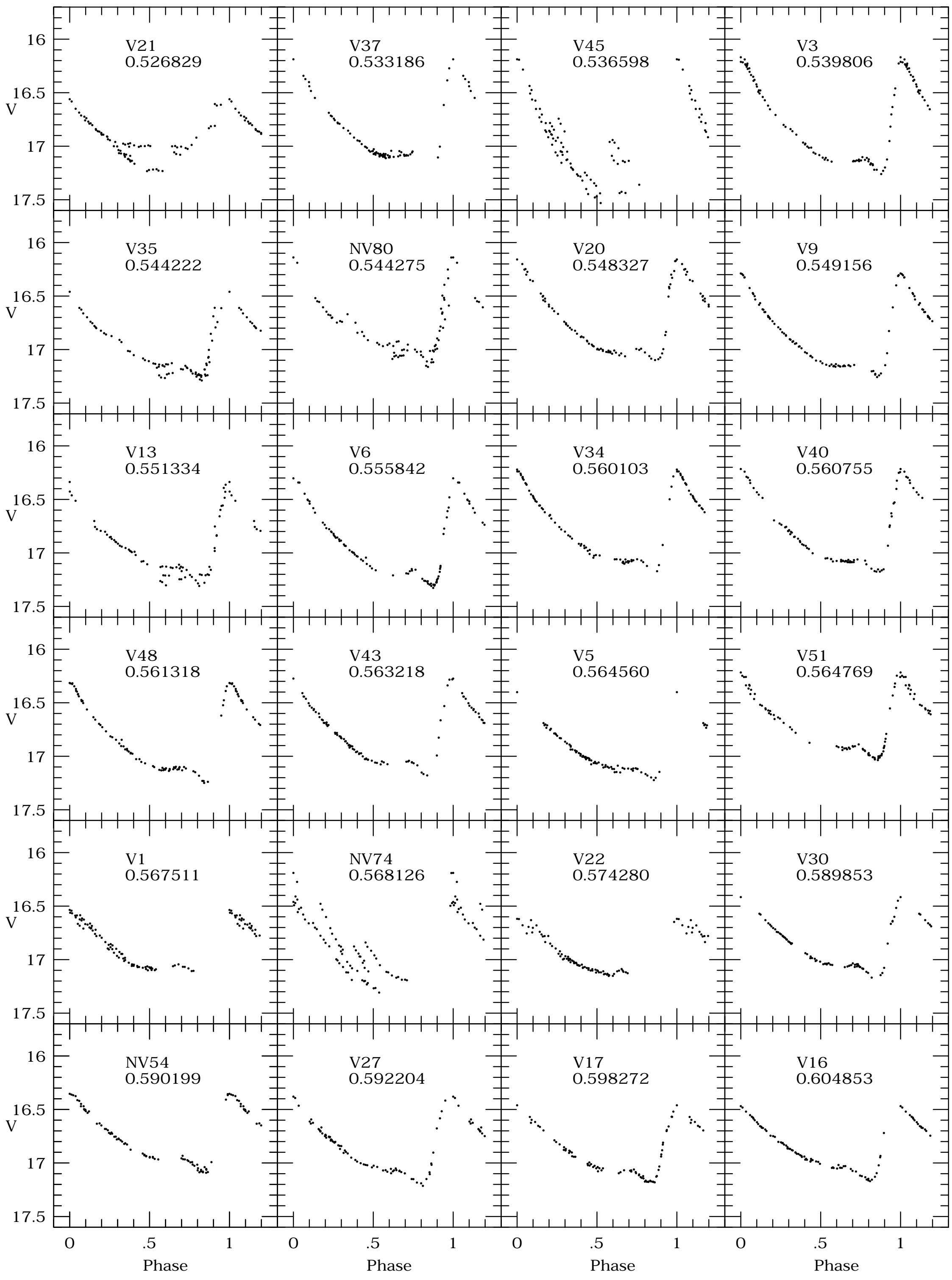

FIG. 2.—*Continued*

ϕ_{21}, and ϕ_{31}. The errors presented in Table 2 are calculated from the formal errors of the Fourier coefficients using the error propagation law.

Using the formula of Kovács (1998a) we can also compute the absolute magnitude $M_V^{\rm Ko}$:

$$M_V^{\rm Ko} = 1.261 - 0.961P_1 - 0.004\phi_{21} - 4.447A_4 \,. \quad (9)$$

The above equation is calibrated using luminosities derived with the Baade-Wesselink method. It implies relatively faint absolute magnitudes of RR Lyr stars. We decided also to use the values of log $L/L_\odot$ of RRc stars for computing the other way absolute visual magnitudes of RRc stars in NGC 6934. The values of M_V (presented in the last column of Table 2) were calculated assuming a value of 4.70 for $M_{\rm bol}$ of the Sun and using the bolometric correction BC = 0.06[Fe/H] + 0.06 adopted after Sandage & Cacciari (1990).

From a sample of 10 RRc stars detected in NGC 6934 we

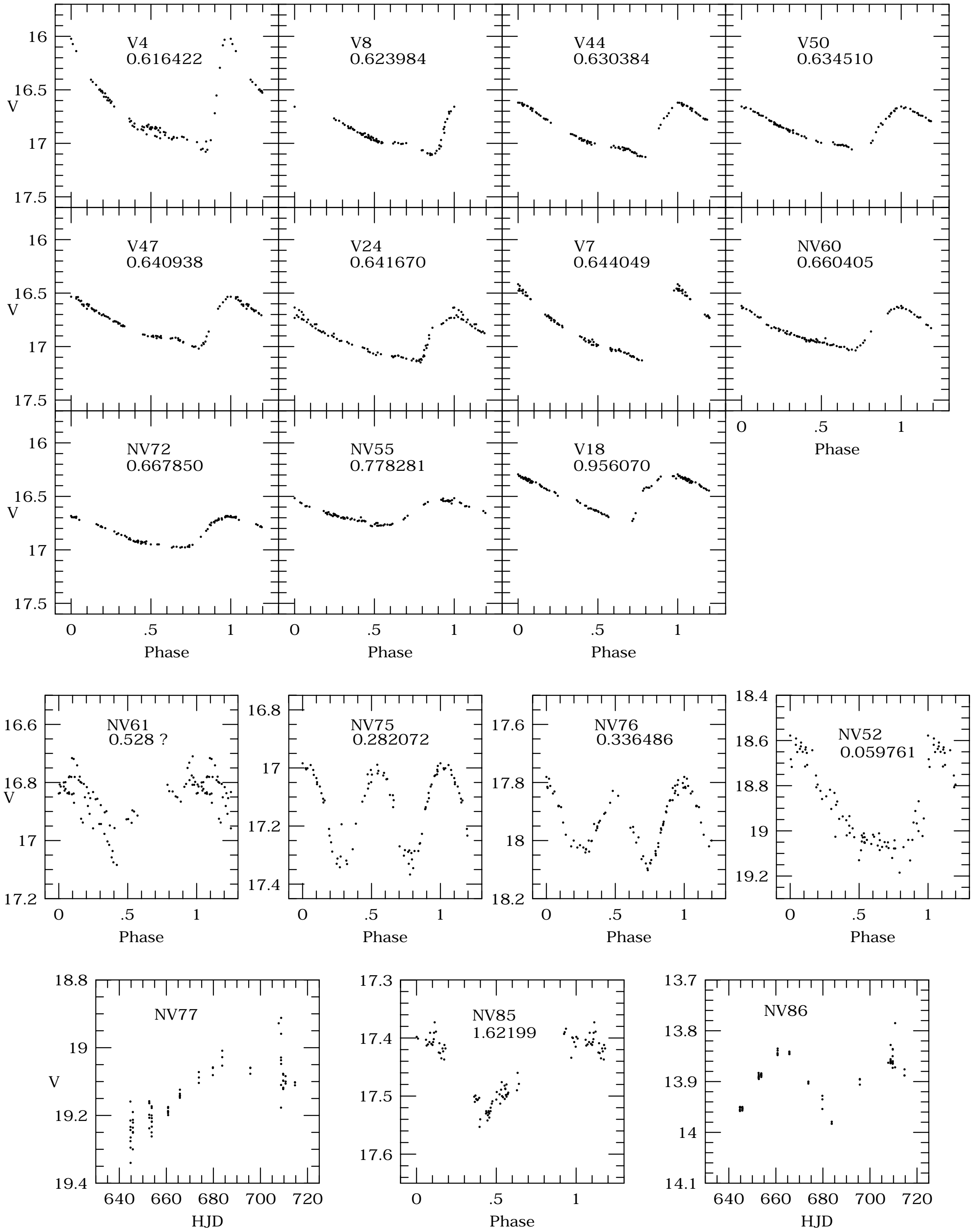

FIG. 2.—*Continued*

excluded two variables for which only ISIS photometry is available. Four out of the remaining eight stars have errors of ϕ_{31} larger than 0.2 and these objects were also excluded from further analysis. For the four retained objects the mean values of the mass, luminosity, effective temperature and helium abundance are 0.63 ± 0.06 $M_{\odot}$, $\log L/L_{\odot} = 1.72 \pm 0.01$, $T_{\rm eff} = 7290 \pm 27$, and $Y = 0.27 \pm 0.01$, respectively.

3.1.2. *Variable NV69—A Second Overtone Pulsator?*

In recent years several authors suggested that RRc stars with periods from the range 0.20–0.28 days may be in fact RRe variables, i.e., RR Lyrae stars pulsating in the second overtone. Walker & Nemec (1996) and Kaluzny et al. (2000) found four such candidates in the globular clusters IC 4499 and M5, respectively. Other authors (Alcock et al. 1996; Olech 1997) analyzing the period distributions of RR Lyr variables in LMC and in the Galactic Bulge found three peaks at periods 0.58, 0.34, and 0.28 days, corresponding to the RRab, RRc, and possibly to RRe stars, respectively. Most recently Kiss et al. (1999) presented the detailed study of V2109 Cygni—an ultrashort, small amplitude RRc star.

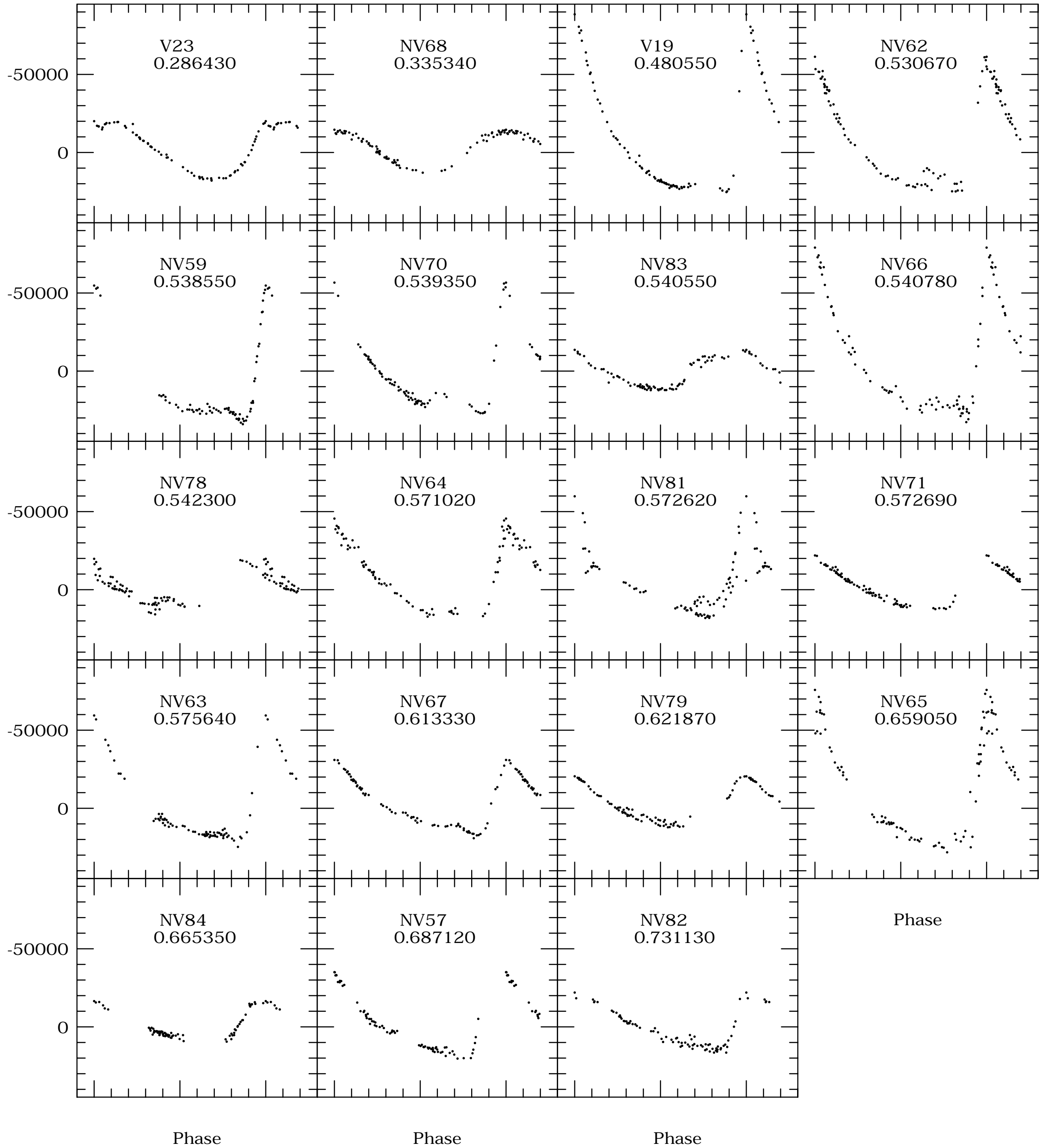

FIG. 3.—*V*-band light curves for variables whose ISIS photometry was retained in differential counts units. The stars are plotted according to the increasing period.

They concluded that it occupies different regions on the period-amplitude diagrams than other RRc stars and thus is indeed RRe star. On the other hand Kovács (1998b) presented some arguments against observational evidence for presence of RRe stars with $\langle P \rangle \approx 0.28$ days.

The variable NV69 is the shortest period and lowest amplitude RR Lyr star in NGC 6934. On the period-amplitude relation shown in Figure 7 it occupies completely different location than other RRc stars. We also constructed other diagrams with $R_{21} - \log P$, $\phi_{21} - \log P$ and $\phi_{31} - \log P$ relations, where $R_{21} = A_2/A_1$. These relations are shown in Figure 8, where RRc variables are plotted with open circles and RRab variables with solid triangles. Solid circle denotes the variable NV69 and solid square corresponds to V2109 Cygni. Due to the nearly sinusoidal shape of light curves of RRc stars their phases ϕ_2 and ϕ_3 are often determined with low precision what leads to large uncertainties of ϕ_{21} and ϕ_{31} estimations. Thus, NV69 and V2109 Cygni within error bars may lay close to the whole group of RRc stars in $\phi_{21} - \log P$ and $\phi_{31} - \log P$ plots. Fortunately, the errors of amplitudes A_1 and A_2 are relatively small, and therefore we can determine R_{21} with good precision. On the $R_{21} - \log P$ plot NV69 and V2109 Cyg are located far away from RRc stars what supports hypothesis that they are the second overtone pulsators and belong to RRe variables.

A possible argument against classifying V69 as RRe variable comes from theoretical models published by Bono et al. (1997). These models predict that for periods shorter than about 0.33 days, the amplitude of pulsations observed

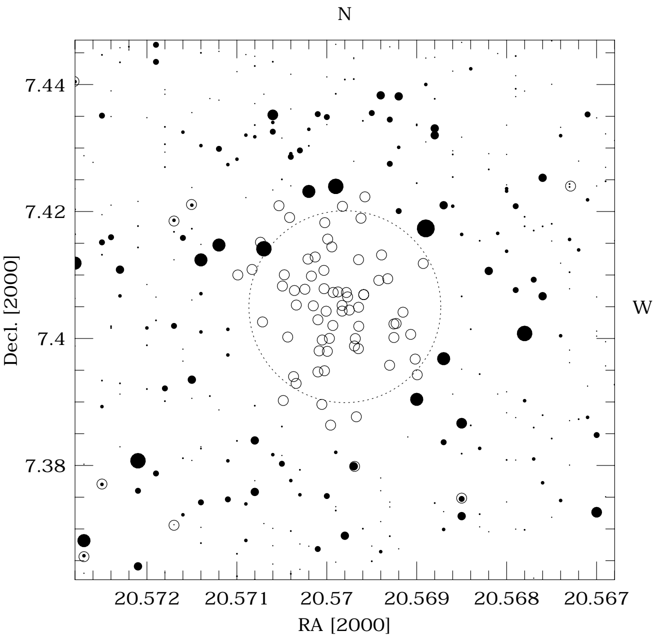

FIG. 4.—The map of the inner NGC 6934 with positions of the variables marked by open circles. The dotted line marks central part of the cluster with $r = 0'.9$. In that part, for clarity, we do not plot the constant stars.

for RRc stars should decrease with decreasing period (the period-amplitude relation becomes parabolic). However, decrease of period is accompanied by increase of $T_{\rm eff}$ and consequently RRc stars with very small amplitudes are expected to be bluer than their counterparts with larger amplitudes. We may comment that average color $(B-V)$ observed for V69 is comparable to colors of 4 other RRc stars from NGC 6934. Specifically, we obtained $\langle B-V \rangle$ equal to 0.25, 0.28, 0.27, and 0.28 for V11, V26, V46, and V53, respectively. For V69 we measured $\langle B-V \rangle = 0.27$.

Concluding this subsection we would like to comment on the shape of the light curve of V69. That light curve shows very low degree of asymmetry. By fitting Fourier series we obtained for it $A_1/A_2 = 0.055$. This seems to contradict classification of V69 as RRe star. Stellingwerf, Gautschy, & Dickens (1987) predicted that RRe stars should have light curves that have "a much sharper peak at maximum light than the first-overtone pulsators ...". However, their paper includes also a cautionary remark that " since the amplitude of our model was chosen arbitrarily, we cannot exclude low-amplitude sinusoidal pulsations as type e stars."

3.1.3. *RRab Variables*

Kovács & Jurcsik (1996, 1997, and references quoted therein) have extended the Fourier analysis of Simon & Clement (1993) into RRab stars. They derived the formulae that connect the periods, amplitudes and phases of RRab stars with their physical parameters such as absolute magnitude, metallicity, intrinsic colors and temperatures. These equations are

$$[{\rm Fe/H}] = -5.038 - 5.394P_0 + 1.345\phi_{31} , \quad (10)$$

$$M_V = 1.221 - 1.396P_0 - 0.477A_1 + 0.103\phi_{31} , \quad (11)$$

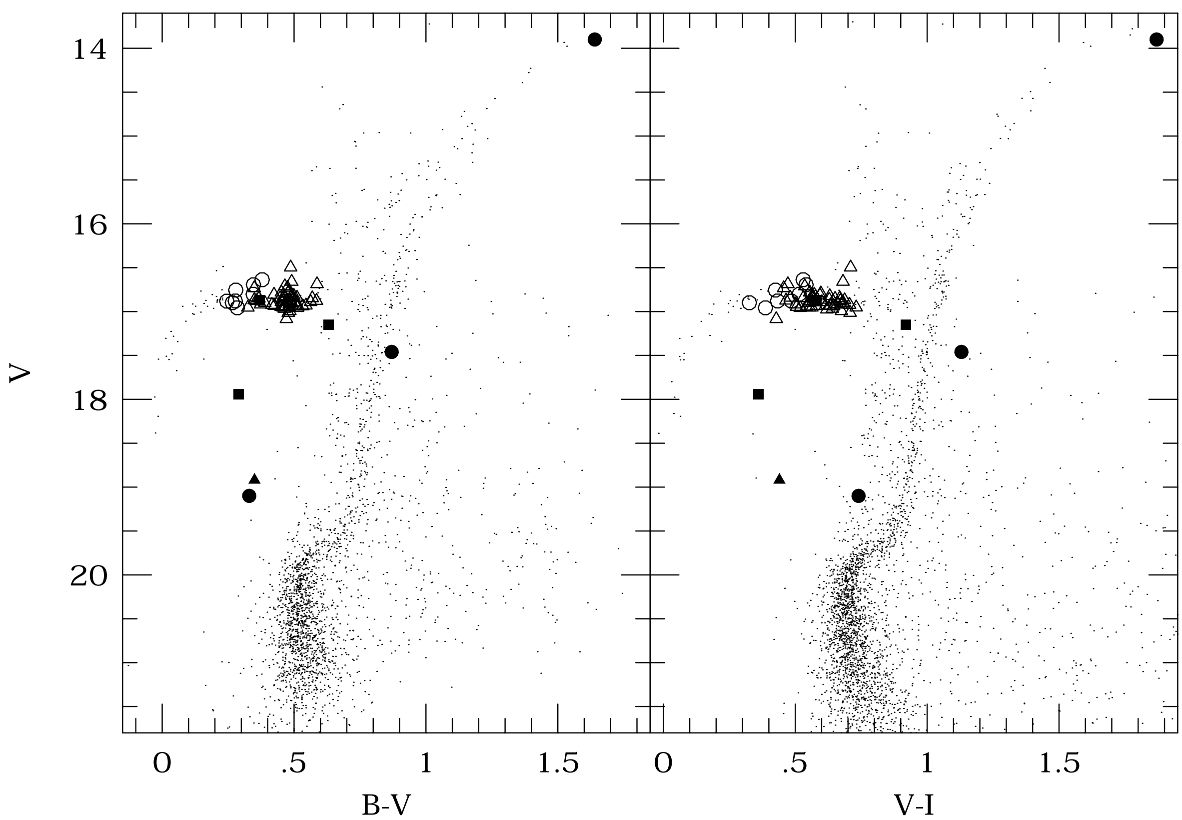

FIG. 5.—The $(V, B-V)$ and $(V, V-I)$ color-magnitude diagrams for NGC 6934. Open circles and triangles denote the RRc and RRab stars, respectively. Filled squares denote W UMa stars, filled triangle denotes SX Phe variable and filled circles denote other variables.

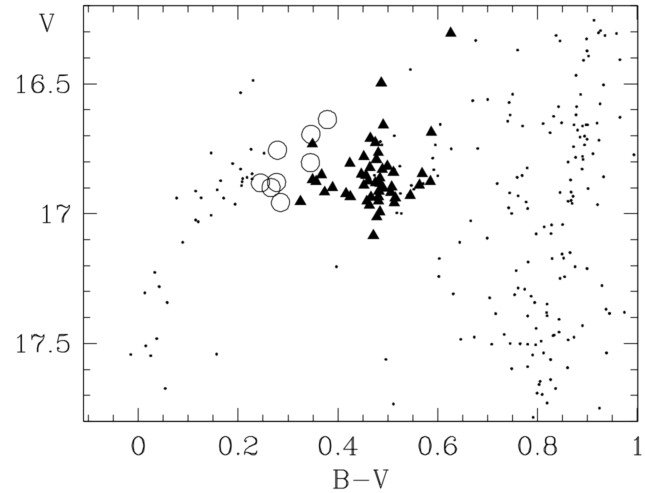

FIG. 6.—Color-magnitude diagram of the horizontal branch region. Open circles and triangles denote the RRc and RRab stars, respectively.

$$V_0 - K_0 = 1.585 + 1.257P_0 - 0.273A_1 - 0.234\phi_{31} + 0.062\phi_{41} , \quad (12)$$

$$\log T_{\rm eff} = 3.9291 - 0.1112(V_0 - K_0) - 0.0032[{\rm Fe/H}] , \quad (13)$$

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

The above equations are valid only for RRab stars with regular light curves, i.e., variables with a deviation parameter D_m smaller than 3 (see Kovács & Kanbur 1998 for definition of D_m). Table 3 summarizes the results obtained using equations (10)–(13). This table does not contain the variable NV61 due to its poor light curve and uncertain period. The parameters such as ϕ_{31}, ϕ_{41}, M_V, ΔM_V, [Fe/H], and Δ[Fe/H] are listed only for stars with $D_m < 5$.[10] The mean values of the absolute magnitude, metallicity

[10] Most of objects with $D_m > 5$ are likely Blazhko variables i.e., RRab stars showing modulation of light curves on a timescale of the order of a few weeks.

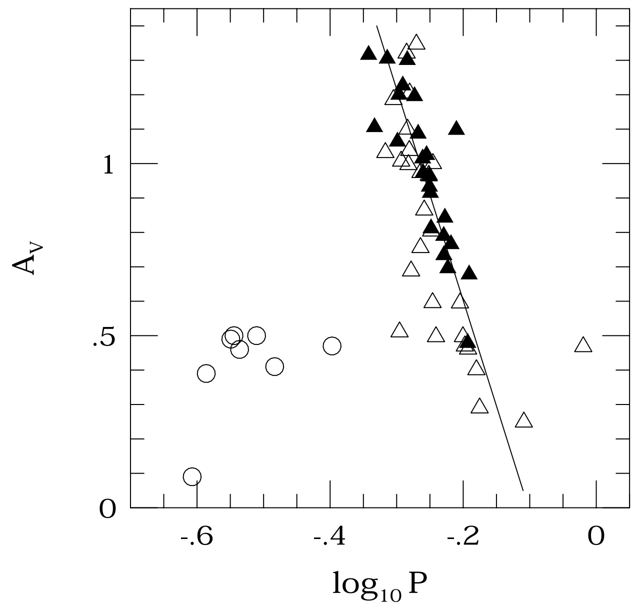

FIG. 7.—Period-amplitude diagram for RRab stars with $D_m < 3$ (*solid triangles*), RRab stars wit $D_m > 3$ (*open triangles*) and RRc stars (*open circles*). The solid line represents a linear fit to RRab variables in M3 (Kaluzny et al. 1998a).

and effective temperature for 24 stars with $D_m < 3$ are $M_V = 0.81 \pm 0.01$, [Fe/H] $= -1.31 \pm 0.04$ and $T_{\rm eff} = 6455 \pm 18$, respectively.

One can see that the value of [Fe/H] derived from equation (10) differs by about 0.2 dex from the value adopted by Harris (1996). On the other hand we should remember that the metallicity computed from equation (10) is in the scale of Jurcsik (1995) which is connected with scale of Zinn & West (1984) by the formula:

$$[{\rm Fe/H}]_{\rm Jurcsik} = 1.431[{\rm Fe/H}]_{\rm ZW} + 0.880 , \quad (14)$$

and thus [Fe/H] $= -1.31$ on the Jurcsik's scale corresponds to [Fe/H] $= -1.53$ on the Zinn & West scale. Therefore, our final determination of metallicity of RR Lyr

TABLE 2

PARAMETERS FOR THE RRc VARIABLES IN NGC 6934

Star	A_0	A_1	ϕ_{21}	ϕ_{31}	M ($M_\odot$)	log L	$T_{\rm eff}$ (K)	Y	$M_V^{\rm Ko}$	M_V
V11	16.895	0.259	3.076	6.077	0.633	1.709	7335	0.272	0.747	0.460
	±0.000	±0.002	±0.040	±0.070	±0.011	±0.004	±6	±0.002	±0.007	
V26	16.634	0.218	3.027	6.039	0.620	1.684	7391	0.279	0.765	0.8727
	±0.000	±0.002	±0.058	±0.211	±0.027	±0.012	±20	±0.007	±0.008	
V46	16.761	0.209	2.734	6.234	0.629	1.728	7280	0.267	0.791	0.412
	±0.000	±0.002	±0.111	±0.120	±0.019	±0.007	±11	±0.003	±0.011	
V49	16.817	0.234	2.804	5.135	0.772	1.728	7325	0.261	0.767	0.412
	±0.000	±0.003	±0.080	±0.101	±0.020	±0.006	±9	±0.003	±0.013	
NV53......	16.878	0.241	2.896	5.861	0.639	1.681	7406	0.279	0.816	0.530
	±0.000	±0.004	±0.082	±0.278	±0.045	±0.016	±26	±0.008	±0.018	
NV56......	16.634	0.218	3.027	6.039	0.620	1.684	7391	0.279	0.765	0.522
	±0.000	±0.009	±0.529	±1.024	±0.161	±0.059	±97	±0.029	±0.081	
NV58......	16.698	0.231	4.193	7.807	0.468	1.726	7218	0.276	0.649	0.417
	±0.000	±0.001	±0.112	±0.137	±0.016	±0.008	±12	±0.004	±0.009	
NV69......	16.897	0.045	3.541	3.678	1.036	1.747	7341	0.247	0.859	0.365
	±0.000	±0.001	±0.483	±1.268	±0.333	±0.074	±119	±0.032	±0.022	

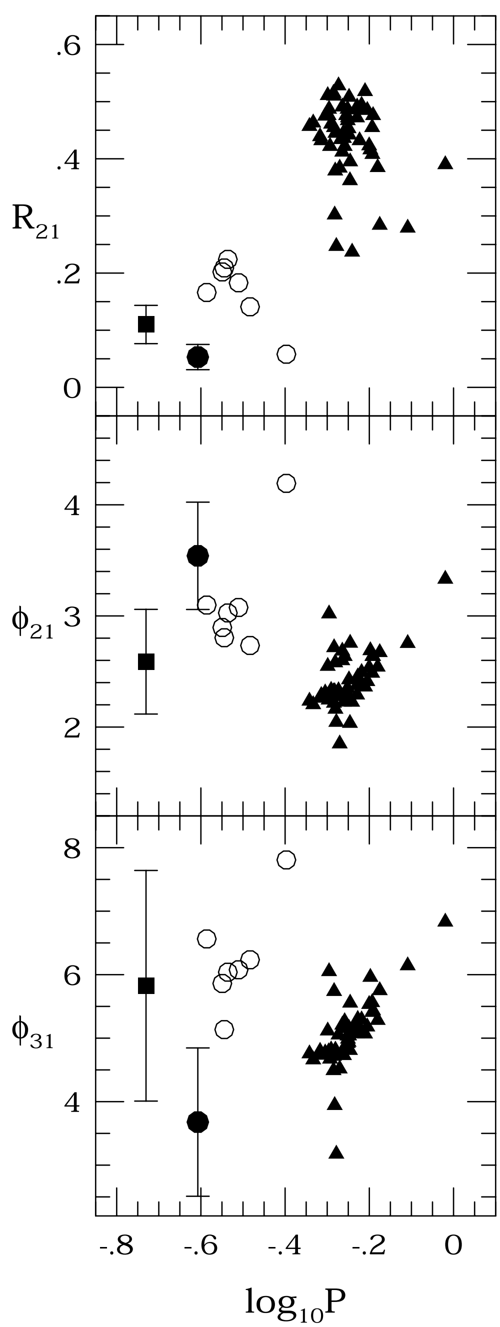

FIG. 8.—Amplitude ratio and Fourier phase differences as a function of period. RRc variables are plotted with open circles and RRab variables with solid triangles. Filled circle denotes the variable NV69, and filled square denotes V2109 Cygni.

from NGC 6934 on the Zinn & West (1984) scale is [Fe/H] $= -1.53 \pm 0.03$. This result agrees very well with the value adopted by Harris (1996; [Fe/H] $= -1.54$) in his catalog of globular clusters.

3.2. *Reddening of NGC 6934*

Previous determinations of reddening for NGC 6934 range from $E(B-V) = 0.05$ (Piotto et al. 1999) to $E(B-V) = 0.20$ (Harris & Racine 1973). The reddening map of Schlegel et al. (1998) gives $E(B-V) = 0.11$ for the cluster position. We can provide an independent estimate of reddening for NGC 6934 using the method developed originally by Preston (1964) and Sturch (1966). Following Blanco (1992) for RRab variables the interstellar reddening can be estimated from the formula:

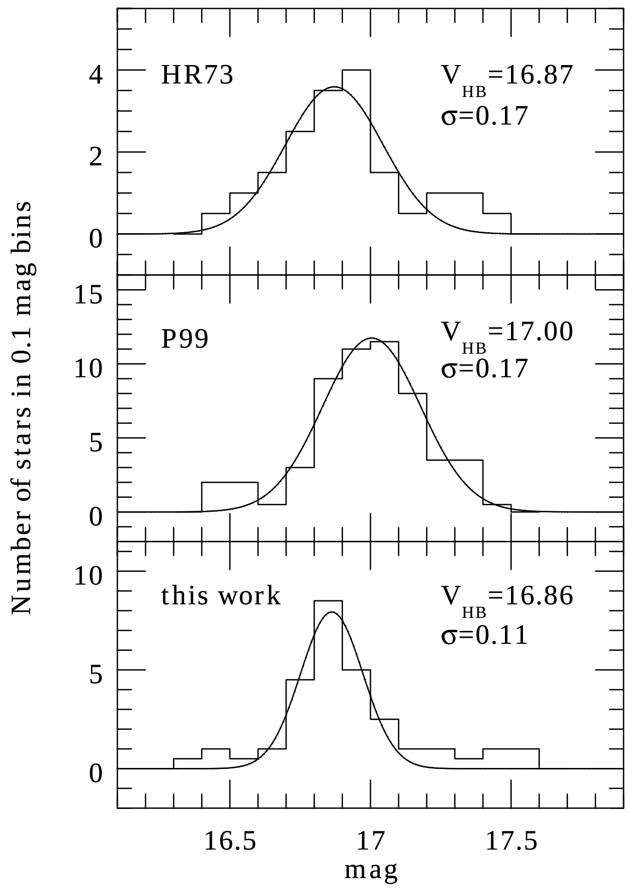

FIG. 9.—The histograms of the distribution in V of the HB stars in the color interval $0.1 < B-V < 0.7$ based on color magnitude diagrams presented by Harris & Racine (1973), Piotto et al. (1999), and in this work.

$$E(B-V) = \langle B-V \rangle_{\Phi(0.5-0.8)} + 0.01222\Delta S - 0.00045(\Delta S)^2 - 0.185P - 0.356 , \quad (15)$$

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

$$[\mathrm{Fe/H}] = -0.408 - 0.158\Delta S . \quad (16)$$

From our sample of RRab variables we have selected 39 stars for which with at least four determinations of $B-V$ color in the phase interval 0.5–0.8 are available. For these stars we have used equation (15) and derived $E(B-V) = 0.091 \pm 0.006$ for the assumed [Fe/H] $= -1.54$.

3.3. *Distance Modulus*

Recent determination of distance modulus for NGC 6934 was published by Piotto et al. (1999). They used an observed V magnitude level of the zero age horizontal branch (V_{ZAHB}) as a distance indicator and obtained for the cluster $(m - M)_V = 16.37$. That estimate is based on a measured value $V_{\mathrm{ZAHB}} = 17.05 \pm 0.04$ and an adopted $M_V^{\mathrm{ZAHB}} = 0.68$. The value of V_{ZAHB} obtained for NGC 6934 by Piotto et al.

(1999) is noticeably fainter than earlier estimates available in literature.[11] Harris & Racine (1973) used their photographic data to obtain $V_{HB} = 16.82 \pm 0.02$, while Brocato et al. (1998) listed $V_{HB} = 16.90 \pm 0.05$ based on the CCD data. To clarify this apparent discrepancy we used our photometry to derive yet another estimate of the horizontal branch level for the cluster. A histogram showing distribution of V magnitudes for nonvariable HB stars from our sample with $0.1 \leq (B-V) \leq 0.7$ (the same color interval was used by Piotto et al. 1999) is presented in Figure 9. The peak of that histogram is located at $V_{HB} = 16.86 \pm 0.05$.

We conclude that the zero point of the *HST*-based photometry presented by Piotto et al. (1999) is shifted by about 0.19 mag relatively to three independent ground-based studies of NGC 6934. That would imply downward revision of the distance modulus advocated by Piotto et al. (1999) to $(m-M)_V = 16.18 \pm 0.05$ if we adopt $V_{HB} = 16.86$ as indicated by our data (the quoted error includes only uncertainty of measured value of V_{HB}).

[11] Piotto et al. (1999) assume that peak of the magnitude distribution of HB stars is equivalent to the level of the ZAHB. They argue that such approach is justified by a fact that globular clusters HB stars spent most of their evolution on the ZAHB.

TABLE 3

Parameters for the RRab Variables in NGC 6934

Star	P (days)	A_0	A_1	ϕ_{31}	ϕ_{41}	M_V	σ_{M_V}	[Fe/H]	$\sigma_{[Fe/H]}$	T_{eff} (K)	D_m
V1	0.567511	16.903	0.255	4.810	1.259	0.807	0.176	−1.630	0.992	6353	3.87
V2	0.481947	16.933	0.381	...	...	...	...	...	...	...	14.49
V3	0.539850	16.894	0.376	4.735	1.195	0.780	0.081	−1.581	0.099	6439	2.49
V4	0.616310	16.690	0.345	5.069	1.277	0.723	0.089	−1.544	0.174	6386	2.96
V5	0.564507	16.921	0.279	5.158	1.590	0.836	0.091	−1.146	0.235	6447	2.15
V6	0.555866	16.951	0.344	4.884	1.342	0.789	0.084	−1.468	0.064	6429	1.77
V7	0.644068	16.857	0.255	5.434	2.059	0.765	0.103	−1.203	0.510	6333	1.11
V8	0.623984	16.869	0.203	...	...	...	...	...	...	...	21.67
V9	0.549104	16.912	0.330	4.729	1.080	0.789	0.082	−1.639	0.068	6412	2.59
V10	0.519949	16.895	0.439	4.717	1.118	0.776	0.079	−1.498	0.100	6506	1.95
V12	0.464215	16.968	0.403	4.661	0.958	0.865	0.078	−1.272	0.057	6591	1.16
V13	0.551334	16.956	0.300	5.263	1.913	0.855	0.092	−0.933	0.185	6481	3.97
V14	0.522084	16.898	0.398	...	...	...	...	...	...	...	61.88
V16	0.604817	16.863	0.261	5.291	1.837	0.803	0.093	−1.184	0.052	6383	1.73
V17	0.598272	16.902	0.260	5.162	1.880	0.799	0.091	−1.322	0.092	6349	1.34
V18	0.955969	16.512	0.196	...	...	...	...	...	...	...	38.63
V20	0.548327	16.786	0.346	4.829	1.187	0.793	0.083	−1.501	0.090	6441	1.70
V21	0.526829	16.925	0.243	...	...	...	...	...	...	...	16.14
V22	0.574282	16.927	0.242	...	...	...	...	...	...	...	29.84
V24	0.641670	16.942	0.176	...	...	...	...	...	...	...	18.01
V25	0.509048	16.861	0.376	4.673	1.008	0.817	0.079	−1.499	0.052	6494	3.36
V27	0.592221	16.870	0.297	5.299	1.749	0.804	0.092	−1.105	0.058	6433	1.89
V28	0.485111	16.886	0.483	4.734	1.168	0.806	0.078	−1.287	0.068	6591	2.24
V29	0.454802	17.014	0.470	4.756	1.101	0.856	0.078	−1.094	0.133	6656	1.62
V30	0.589850	16.876	0.275	5.172	1.795	0.804	0.090	−1.264	0.045	6383	0.84
V31	0.505063	16.966	0.400	4.788	1.124	0.823	0.081	−1.322	0.069	6538	0.76
V32	0.511934	16.882	0.420	4.818	1.174	0.807	0.081	−1.320	0.055	6539	1.08
V33	0.518728	16.822	0.407	...	...	...	...	...	...	...	14.74
V34	0.560108	16.839	0.323	...	...	...	...	...	...	...	5.11
V35	0.544222	16.955	0.290	5.208	1.603	0.864	0.091	−0.969	0.193	6504	4.65
V36	0.495659	16.829	0.384	4.771	1.015	0.842	0.081	−1.294	0.095	6554	4.22
V37	0.533173	16.858	0.345	5.053	1.578	0.837	0.087	−1.118	0.144	6501	1.94
V38	0.523553	16.775	0.396	...	...	...	...	...	...	...	12.68
V39	0.502574	16.750	0.357	5.116	1.572	0.881	0.089	−0.868	0.241	6584	2.53
V40	0.560755	16.843	0.339	4.920	1.257	0.788	0.085	−1.445	0.061	6438	1.91
V41	0.520404	16.987	0.378	...	...	...	...	...	...	...	10.42
V42	0.524235	16.984	0.406	4.814	0.973	0.796	0.082	−1.390	0.118	6530	4.36
V43	0.563180	16.846	0.317	4.938	1.344	0.797	0.086	−1.435	0.056	6420	1.63
V44	0.630373	16.902	0.193	...	...	...	...	...	...	...	13.87
V45	0.536598	16.914	0.532	...	...	...	...	...	...	...	21.12
V47	0.640886	16.801	0.181	5.563	2.159	0.819	0.099	−1.013	0.120	6337	2.78
V48	0.561299	16.901	0.319	4.988	1.430	0.804	0.086	−1.356	0.044	6432	0.63
V50	0.634531	16.890	0.174	...	...	...	...	...	...	...	38.68
V51	0.564785	16.744	0.257	...	...	...	...	...	...	...	8.72
NV54	0.590199	16.799	0.253	5.072	1.635	0.804	0.090	−1.400	0.121	6356	1.89
NV55	0.778281	16.656	0.112	...	...	...	...	...	...	...	20.39
NV60	0.660405	16.857	0.165	...	...	...	...	...	...	...	29.07
NV72	0.667850	16.851	0.133	5.751	2.200	0.823	0.103	−0.906	0.112	6323	4.68
NV73	0.506209	16.923	0.152	...	...	...	...	...	...	...	11.13
NV74	0.568126	16.782	0.412	...	...	...	...	...	...	...	14.23
NV80	0.544275	16.768	0.302	...	...	...	...	...	...	...	8.90

An alternative way of determining the distance modulus to NGC 6934 is to compare observed magnitudes of RR Lyr stars with their absolute magnitudes. Tables 2 and 3 contain values of M_V derived using three different methods. By adopting absolute magnitudes derived for RRc stars with the Kovacs' calibration (tenth column in Table 2) one obtains $(m - M)_V = 16.01 \pm 0.06$. In case of Simon & Clement calibration (last column in Table 2) we arrive at $(m - M)_V = 16.32 \pm 0.07$. Finally, by using absolute magnitudes derived for RRab variables with Kovacs & Jurcsik calibration (Table 3; only stars with $D_m < 3$ are considered) we get $(m - M)_V = 16.07 \pm 0.09$.

The most secure calibration of absolute magnitudes of RRab stars available at the moment is—in our opinion—that proposed by Gould & Popowski (1998) and based on the statistical-parallax method. Using purely observational data they derived $M_V = 0.77 \pm 0.13$ at [Fe/H] $= -1.60$. After correcting for a 0.01 mag offset reflecting slightly lower metallicity of the cluster we may adopt $M_V = 0.78 \pm 0.13$ for RRab stars in NGV 6934 (we used relation $\Delta M_V/\Delta$[Fe/H] $= 0.18$ following Fernley et al. 1997). From our sample of cluster RRab stars we selected 24 objects with stable light curves and obtained for them an average value of $\langle V \rangle = 16.873 \pm 0.017$. This in turn leads to an apparent distance modulus of the cluster $(m - M)_V = 16.87 - 0.77 = 16.10 \pm 0.13$, which is very close to the value $(m - M)_V = 16.13$ listed in the catalog of Harris (1996).

Concluding this section we note that four out of five methods used here to estimate an apparent distance modulus of NGC 6934 give results which are consistent with each other within quoted errors. Only the method based on calculation of M_V for RRc stars with formulas given by Simon & Clement (1993) leads to a relatively larger distance modulus of the cluster. By taking an unweighted mean of four consistent determinations we obtain $(m - M)_V = 16.09 \pm 0.06$ for NGC 6934.

3.4. *W UMa Variables*

We have used the absolute brightness calibration for W UMa-type binaries (Rucinski 2000) to estimate the absolute magnitudes M_V for the two newly discovered contact binaries in NGC 6934. Rucinski's equation gives the relation between M_V at maximum light and the period, unreddened color $(B-V)_0$ and metallicity:

$$M_V = -4.44 \log P + 3.02(B - V)_0 + 0.12 \ . \quad (17)$$

We adopted $E(B-V) = 0.09$ for both stars. The apparent distance modulus for each system was calculated as the difference between its observed V_{max} magnitude and M_V derived from equation (17). The last column of Table 4 presents the resulting values of distance modulus. Both binaries are most likely the foreground variables because their estimated distance moduli are much smaller than distance modulus of NGC 6934.

TABLE 4

BASIC ELEMENTS OF W UMa VARIABLES IN NGC 6934

Star	P (days)	V_{max}	B_{max}	$(B-V)_{max}$	$(m - M)_V$
NV75......	0.28207	16.99	17.62	0.63	12.82
NV76......	0.33649	17.80	18.08	0.28	15.02

3.5. *Other Variables*

A SX Phe variable NV52 is located in the blue straggler region of the cluster color-magnitude diagram (see Fig. 5). Large A_V amplitude and asymmetrical light curve indicates that NV52 is a fundamental mode pulsator. Thus, we can use the relation of McNamara (1997) connecting the absolute magnitude of the fundamental SX Phe pulsators with their periods:

$$M_V = -3.725 \cdot \log P_0 - 1.933 \ . \quad (18)$$

The resulting absolute magnitude of NV52 is $M_V = 2.63$ what leads to estimated distance modulus $(m - M)_V = 16.29$. Such a value is consistent with the assumed cluster membership of the variable.

The variable NV77 is a rather faint and blue object and it possibly belongs to the group of the cluster blue or yellow stragglers. It is hard to say based on our data if there is any periodicity in its light curve. The variable is located in the outer part of the cluster but that location certainly does not preclude cluster membership. We note that the variable is bluer than the cluster turnoff on the $V/B-V$ diagram while it is redder than the cluster turnoff on the $V/V-I$ diagram. This suggests that NV77 may be a composite system.

The variable NV85 is located on the red side of the cluster giant branch and about 0.5 mag below its horizontal branch (see Fig. 5). Our data are best phased with the period $P = 1.622$ days but $P = 2.606$ days is also possible. Further data are needed to clarify type of variability and membership status of that star.

The variable NV86 is located at the tip of the cluster red giant branch. Our data indicate presence of variations with a period close to 49 days. The star belongs most likely to semiregular, bright variables, which are common among AGB stars in globular clusters.

4. CONCLUSIONS

We have presented the photometry of 85 variables in the globular cluster NGC 6934. The photometry was obtained using the newly developed image subtraction method (Alard & Lupton 1998; Alard 2000). As first demonstrated by Olech et al. (1999b), image subtraction method provides a very powerful tool for extracting photometry of variables located in central regions of globular clusters. As many as 35 variables from our sample are new discoveries. Among these newly identified stars we have detected 24 RRab stars, five RRc stars, two eclipsing W UMa systems, one SX Phe star, and three other variables. Our total sample contains photometry for 68 RRab and 10 RRc stars.

Suntzeff et al. (1991) estimated that only 6% of the RR Lyr variables hosted by galactic GCs remain to be discovered. The case of NGC 6934 and recent results obtained by our group for some other clusters (M5, M55, and NGC 6362) shows that incompleteness of available samples is much higher. In case of NGC 6934 we have identified 29 new RR Lyr stars, what amounts up to about 37% of the total sample for this cluster.

The periods of RRab variables from NGC 6934 are between 0.4548 and 0.956 days with the mean value of 0.574 days. Periods of RRc stars are between 0.2470 and 0.4008 days with the mean at 0.310 days.

Only four RRc stars from our sample have the light curves with quality good enough for computing their physical parameters from the Fourier decomposition coefficients.

The mean values of the mass, luminosity, effective temperature, and helium abundance for these RRc stars are $0.63 \pm 0.06\ M_{\odot}$, $\log L/L_{\odot} = 1.72 \pm 0.01$, $T_{\rm eff} = 7290 \pm 27$, and $Y = 0.27 \pm 0.01$, respectively.

Out of 69 RRab variables only 24 showed stable light curves during our observations. For this subsample we used the method developed by Kovács & Jurcsik (1996, 1997) to derive values of the absolute magnitude, metallicity and effective temperature which are equal to $M_V = 0.81 \pm 0.01$, [Fe/H] $= -1.53 \pm 0.04$ (Zinn-West scale) and $T_{\rm eff} = 6455 \pm 18$, respectively.

From the $B-V$ color at minimum light of the RRab variables we obtained the color excess to NGC 6934 equal to $E(B-V) = 0.09 \pm 0.01$. It is marginally consistent with the recent determination of Piotto et al. (1999), who derived $E(B-V) = 0.05 \pm 0.02$, but agrees well with a value $E(B-V) = 0.11$ obtained using the reddening map of Schlegel et al. (1998).

We obtained five estimates of an apparent distance modulus of the cluster using various calibrations of M_V for RR Lyr stars and HB stars. A calibration based on statistical-parallax method (Gould & Popowski 1998) which is preferred by us leads to $(m-M)_V = 16.10 \pm 0.13$. We noted a likely error in the zero point of photometry published for the cluster by Piotto et al. (1999).

Among cluster RR Lyr stars we have detected a short period and low amplitude variable whose characteristic make it a good candidate for the second overtone pulsator.

Both eclipsing variables detected in this search are W UMa-type systems and both most likely are the foreground stars.

The magnitude and the color of the single detected SX Phe variable suggest that it belongs to the cluster blue stragglers group. Its distance modulus computed based on relation of McNamara (1997) is compatible with the cluster membership of that star.

Our sample of newly identified variables includes also one AGB star with possible period $P \approx 49$ days, one periodic variable with $P = 1.62$ days or $P = 2.61$ days and one star which is a likely binary but for which we have no clue neither for its type of variability nor for possible periodicity of light variations.

We thank Martin Krockenberger and Dimitar Sasselov for taking significant part of the data used in this paper. We thank the referee for useful comments. We are indebted to Alex Schwarzenberg-Czerny for his excellent period finding software and for many stimulating discussions. We thank Christophe Alard for his help with ISIS. J. K. and A. O. were supported by the Polish Committee of Scientific Research through grant 2P03D–003–17 and by NSF grant AST–9819787 to Bohdan Paczyński. K. Z. S. was supported by NASA through Hubble Fellowship grant HF-01124.01-A from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

REFERENCES

Alard, C. 2000, A&AS, 144, 363
Alard, C., & Lupton, R. H. 1998, ApJ, 503, 325
Alcock, C., et al. 1996, AJ, 111, 1146
Blanco, V. 1992, AJ, 104, 734
Bono, G., Caputo, F., Castellani, V., & Marconi, M. 1997, A&AS, 121, 327
Brocato, E., Buonanno, R., Malakhova, Y., & Piersimoni, A. M. 1998, A&A, 311, 778
Fernley, J., Carney, B., Skillen, I., Cacciari, C., & Janes, K. 1997, MNRAS, 293, 61
Gould, A., & Popowski, P. 1998, ApJ, 508, 844
Harris, W. E. 1996, AJ, 112, 1487
Harris, W. E., & Racine, R. 1973, AJ, 78, 242
Jurcsik, J. 1995, Acta Astron., 45, 653
Kaluzny, J., Hilditch, R. W., Clement, C., & Rucinski, S. M. 1998a, MNRAS, 296, 347
Kaluzny, J., Olech, A., Thompson, I., Pych, W., Krzeminski, W., & Schwarzenberg-Czerny, A. 2000, A&AS, 143, 215
Kaluzny, J., Stanek, K. Z., Krockenberger, M., Sasselov, D. D., Tonry, J. L., & Mateo, M. M. 1998b, AJ, 115, 1016
Kiss, L. L., Csák, B., Thomson, J. R., & Vinkó, J. 1999, A&A, 345, 149
Kovács, G. 1998a, Mem. Soc. Astron. Italiana, 69, 49
———. 1998b, ASP Conf. Ser. 135, A Half Century of Stellar Pulsation Interpretations: A Tribute To Arthur N. Cox, ed. P. A. Bradley & J. A. Guzik (San Francisco: ASP), 52
Kovács, G., & Jurcsik, J. 1996, ApJ, 466, L17
———. 1997, A&A, 322, 218
Kovács, G., & Kanbur, S. M. 1998, MNRAS, 295, 834
Landolt, A. 1992, AJ, 104, 340
Mazur, B., Kaluzny, J., & Krzeminski, W. 1999, MNRAS, 306, 727
McNamara, D. H. 1997, PASP, 109, 1221
Monet, D., et al. 1996, USNO-SA2.0 (Washington: US Naval Obs.)
Olech, A. 1997, Acta Astron., 47, 183
Olech, A., Kaluzny, J., Thompson, I. B., Pych, W., Krzeminski, W., & Schwarzenberg-Czerny, A. 1999a, AJ, 118, 442
Olech, A., Woźniak, P. R., Alard, C., Kaluzny, J., & Thompson, I. B. 1999b, MNRAS, 310, 759
Piotto, G., Zoccali, M., King, I. R., Djorgovski, S. G., Sosin, C., Dorman, B., Rich, R. M., & Meylan, G. 1999, AJ, 117, 264
Preston, G. W. 1964, ARA&A, 2, 23
Rucinski, S. M. 2000, AJ, 120, 319
Sandage, A., & Cacciari, C. 1990, ApJ, 350, 645
Sawyer-Hogg, H., & Wehlau, A. 1980, AJ, 85, 148
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Schwarzenberg-Czerny, A. 1997, ApJ, 489, 941
Schwarzenberg-Czerny, A., & Kaluzny, J. 1998, MNRAS, 300, 251
Simon, N. R., & Clement, C. M. 1993, ApJ, 410, 526
Smith, H. A. 1995, RR Lyr Stars (Cambridge: Cambridge Univ. Press)
Stanek, K. Z., Kaluzny, J., Krockenberger, M., Sasselov, D. D., Tonry, J. L., & Mateo, M. 1998, AJ, 115, 1894
Stellingwerf, R. F., Gautschy, A., & Dickens, R. J. 1987, ApJ, 313, L75
Stetson, P. B. 1987, PASP, 99, 191
———. 1991, ASP Conf. Ser. 25, Astronomical Data Analysis, Software and Systems I, ed. D. M. Worrall, C. Biemesderfer, & J. Barnes (San Francisco: ASP), 297
Sturch, C. 1986, ApJ, 143, 774
Suntzeff, N. B., Kinman, T. D., & Kraft, R. P. 1991, ApJ, 367, 528
Walker, A. R., & Nemec, J. M. 1996, AJ, 112, 2026
Zinn, R., & West, M. J. 1984, ApJS, 55, 45