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VARIABLE STARS IN THE GLOBULAR CLUSTER M14

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ABSTRACT

Using an image subtraction method we have searched for variable stars in the globular cluster M14. We confirmed 62 previously known catalogued variables. In addition to the previoulsy known variables we have identified 71 new variables. We have confirmed the periods of most of the cataloged variables with just a few exceptions. Of the the total number of confirmed variables, we found a total of 112 RR Lyrae stars, several of which exhibited the Blazhko Effect. Of the total we classified 55 RR0, 57 RR1, 19 variables with periods greater than 2 days, a W UMa contact binary, and an SX Phe star. We present the periods of previously found variables as well as the periods, classification, and lightcurves of the newly discovered variables.

Subject headings: stars: variables: general–Galaxy: globular clusters: individual: M14

1. INTRODUCTION

Globular clusters provide a laboratory for studying stellar evolution of a coeval population of stars. This allows for the examination of various evolutionary phases of the stellar population. Of particular interest are post main sequence variable stars in globular clusters. The most common type of variable stars in globular clusters are RR Lyrae stars. These stars are horizontal branch stars that lie within the instability strip. Only low metalicity clusters contain RR Lyrae stars. Having a metallicity of [Fe/H]=-1.39 the globular cluster M14 is one such cluster (Harris 1996).

M14 (NGC 6402) is a globular cluster with many known variable stars. Clement's Catalogue of Variable Stars in Globular Clusters (Clement et al. 2001) reports 90 possible variables of which 61 have determined periods. 54 of these have been identified as RR Lyraes, 6 as Cepheids or RVTau, 6 as longterm or irregular variables, and no eclipsing binaries or SX Phoenix stars. Most of these were found by Wehlau & Froelich (1994) using photographic photometry on data obtained between 1912 and 1980 mostly by H. S. Hogg (Sawyer-Hogg & Wehlau 1968). Additional unpublished studies have also been conducted which do not appear in Clement's catalogue, and have found several additional variables (Jacobs 2004). M14 lies near the celestial equator so is visible in both the southern and northern hemisphere. Given our extended access to telescopes in each hemisphere, M14 was an ideal candidate to search for variables.

In this study we use an image subtraction method developed by Alard (2000) to search the central $13 \times 13'$ of globular cluster M14 for variable stars from observations obtained in June and July of 2010. With the combination of better resolution CCD images and image subtraction, we can better resolve variables dimmer and/or closer to the crowded field in the core as compared to previous photographic studies. In doing so, we have confirmed many of the previously found variables, confirmed or have better determined periods, as well as identified a large number of new variables in the cluster.

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2. OBSERVATIONS AND REDUCTION

Image frames were obtained using two different telescopes, one at Kitt Peak National Observatory (KPNO) and the other at Cerro Tololo Interamerican Observatory (CTIO). On the nights of 6, 9, 16, 18 and 19 June 2010, images were obtained using the KPNO SARA (Southeastern Association for Research in Astronomy) 0.9 meter telescope with an Apogee Alta U42 CCD with a 2048×2048 Kodak e2V CC42-40 with a gain of 1.2 electrons per count, RMS noise of 6.3 electrons, and cooled to a temperature of approximately -30 degrees Celsius. 1×1 binning was used, resulting in a scale of $0.42''$/px and a $13.6 \times 13.6'$ field of view. Typical seeing was $2.2''$ and ranged from $1.5\text{-}3.0''$. Using a Bessel R filter, exposure times were set at a constant 60 seconds to avoid overexposure of the core or bright giants during best possible seeing conditions.

Another set of images were taken with the SARA 0.6 meter telescope at CTIO on 3, 4, 5, 9, 13, and 19 July 2010 using an Apogee Alta E6 with a 1024×1024 Kodak KAF1001E chip, with a gain of 1.5 electrons per count, and an RMS noise of 8.9 electrons. The temperature was held at -30 Celsius. 1×1 binning was used with a resulting image scale of $0.6''$/px and a $10 \times 10'$ field of view. Typical seeing was $1.8''$ and ranged from 1.2 to $2.5''$. Using a Bessel V filter, exposure times were set at a constant 150 seconds to achieve similar images as with the KPNO observations. This also ensured that none of the bright stars were overexposed during periods of good seeing. Maxim DL was used to process the CCD images. Each image was debiased, flat-fielded, and dark-subtracted. These processed images were then analyzed using image subtraction.

The autoguider at KPNO was not functioning properly except on the night of 6 June, and was also not functioning properly for a number of nights but the CTIO telescope tracked much better than the KPNO telescope minimizing the importance for autoguiding. Because of this, the CTIO telescope resulted in higher quality images. The KPNO images were only used to examine regions outside of the smaller $10 \times 10'$ field of view of the CTIO telescope.

3. IMAGE SUBTRACTION

Image Subtraction was completed using the ISIS-2.1 package (Alard & Lupton 1998; Alard 2000). The ISIS package consists of six different c-shell scripts: `interp` (registration and interpolation), `ref` (builds reference frame), `subtract` (subtracts images from reference), `detect` (stacks subtracted images), `find` (finds variables above user-defined threshold), and `phot` (makes light curves for found variables), along with three parameter files.

ISIS accounts for changes in seeing conditions by convolving a high quality reference image to the point spread functions of each individual frame and then subtracting the two images to determine if any change in intensity has occurred. These subtracted frames are then combined to create a `var.fits` image which shows the degree of variability across the observation run for each star in the cluster.

The `SIGTHRESH` parameter controls the threshold for which a star is considered a variable. Typical values were for 0.15 for SARA KPNO and 0.05 for SARA CTIO observations, with each producing roughly 270 possible variables. Many of which were due to noise and later eliminated after examining the individual light curves. Values for `SIGTHRESH` were found by looking for the point at which the number of possible objects increased rapidly. A lower `SIGTHRESH` value typically led to a thousand or more false-positives. Once the proper `SIGTHRESH` value was found and false positives eliminated, light curves of relative flux were then generated for each detected variable.

In order to maintain consistent and comparable values for relative flux across nights, one reference image was created using five of the best images from June 6 and this was then used as the reference for all of the KPNO observations. Since the CCD pixel scale is different on the CTIO telescope, a different reference image was used for the CTIO observations. Thirteen of the images with best seeing (average of $1.4''$) were used to create the reference image used for all CTIO observations. The `ref.fits` and `var.fits` images from SARA Cerro Tololo are shown in Figures 1 and 2.

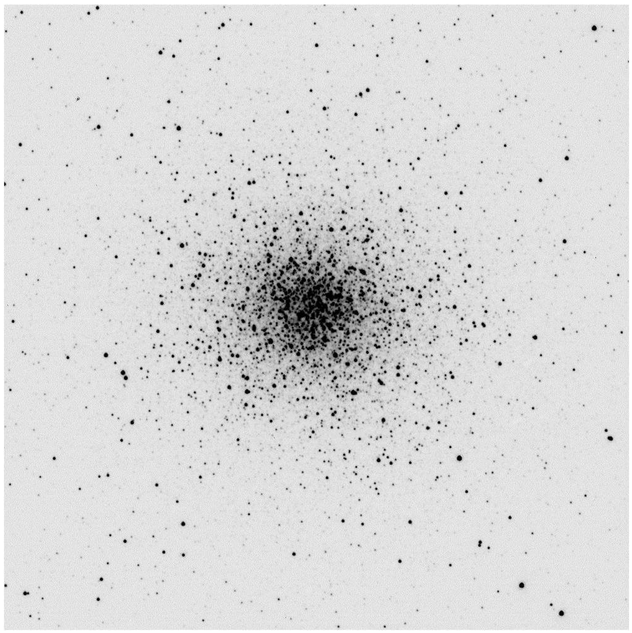

FIG. 1.— The `ref.fits` used for all nights from SARA CTIO. This image is a combination of the best seeing images, with the combined seeing near $1.4''$.

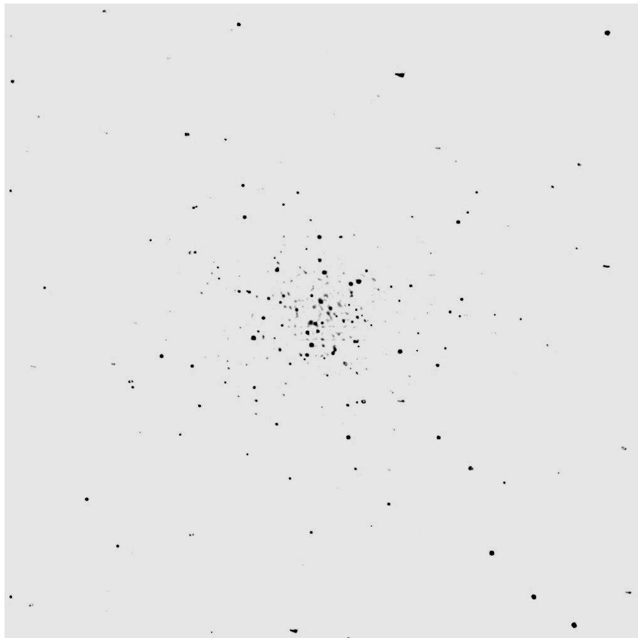

FIG. 2.— The `var.fits` from ISIS for all six nights from SARA CTIO. The relative amount of variation is indicated by the brightness of the star.

4. ANALYSIS

4.1. *Periods*

Periods were determined, when possible, based on combined photometric data from the runs on each of the two telescopes. We used the period finding software `AVE` (Analisis de Variabilidad Estela, Analysis of Estellar Variability) from Grup d'Estudis Astronomics. The software uses the Lomb-Scargle algorithm (Scargle 1982). With data over six full nights, we were able to determine periods of nearly all of the variables having periods under 3 days as can be seen in Table 1 & 2. However, a few of these variables had mulitple possible periods. The periods were generally accurate to 10^{-4} days. Due to our lack of long term obserrvations spanning several months or more, we were unable to accurately ascertain the periods of variables greater than a few days. As we obtain more observations, we hope to determine the periods of these variables as well.

Apart from the longer period variables, we verified the periods of nearly all of the Wehlau & Froelich (1994) variables with only a few exceptions where there were mulitple periods possible. The only RR Lyrae star that we found a significant period differing from Wehlau & Froelich was 77. We found a period of 0.7910 versus 0.3274 days.

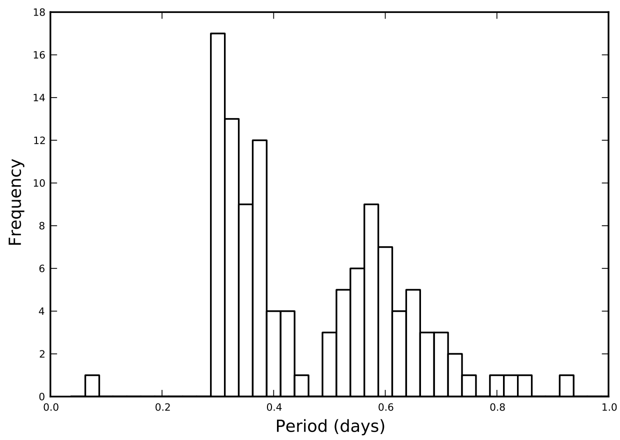

FIG. 3.— A period histogram of observed variables with periods less than 1 day. Note the distinctive break just above 0.4 days. This break separates the RR0 variable stars (right peak) from the RR1 variables (left peak).

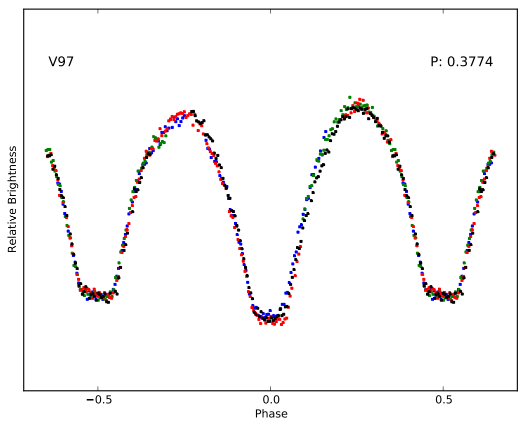

FIG. 5.— Phased light curve of the overcontact eclipsing binary (V97). This binary has a typical W Ursa Majoris light curve.

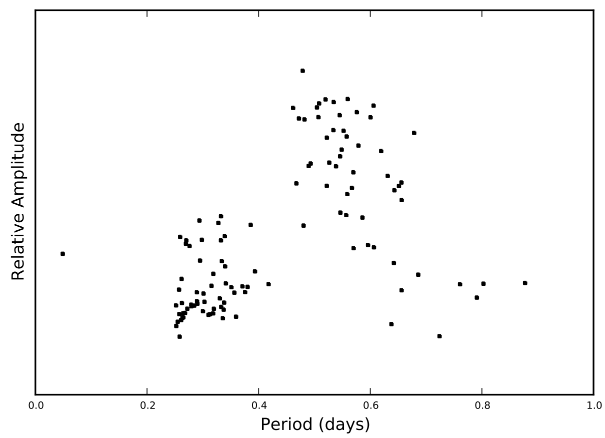

FIG. 4.— A plot of variable period versus amplitude. Similar to figure 3 there is a distinctive separation of the RR0 and RR1 stars.

4.2. *Identification*

Astrometry was done by finding a plate solution using positions from Clement's Catalogue of Variable Stars in Globular Clusters (Clement et al. 2001). We then found additional potential variable matches by comparing our coordinates with those in previous publications. Once these were found, they were confirmed through period comparisons. We compared our results with Wehlau and to the unpublished results of Jacobs (2004). Unfortunately the Jacobs astrometry had an error in the right ascension so we could only make a useful comparison to the Wehlau & Froelich variables in the Jacobs' data set.

In keeping with previously published work, we retained Wehlau & Froelich's number system for stars 1 through 93. Newly discovered variables from this research are in order of increasing right ascension and begin with variable number 94. Of Wehlau & Froelich's 93 variables, we were able to find and confirm 63 of them. Many of those variables we could not confirm within our field of view are listed as *blended* or *NV* (meaning not variable) in Clement et al. (2001), and thus their variablity is either suspect or difficult to determine. Two others variables (V27 and 28) were not observed because they lay outside of our field of view. This left only six remaining variables that we were unable to confirm in the Clement et al. (2001) catalogue (V25, 45, 68, 69, 71 and 86).

TABLE 1
CLASSIFICATION SUMMARY

Variable Type	Count	Period (days)
SX Phoenix	1	0.05
RR0	55	0.2-0.4
RR1	57	0.4-0.8
Eclipsing Binary	1	0.3774
Longer Period	19	$P > 2$ days

4.3. *Classification*

We classified each variable by considering both the shape of the phased light curve, its amplitude, and its period. The relationship between period and variable type is seen in Figure 3. All but one of the varibles shown in this histogram are RR Lyrae variables. The single variable found with a period near 0.05 days is an SX Phoenix star. It is obvious from Figure 3 that there are two distinct types of RR Lyrae stars. Most of our detected variables proved to be RR Lyraes which are then subdivided into the two different types. We used the same notation as Clement et al. (2001) and classified the RR Lyraes as either type RR0 or RR1 for consistency. Besides the obvious difference in periods and appearance of the phased light curves (see Figure 6), the distinction between RR0 and RR1 becomes readily apparent when comparing the amplitude of the magnitude fluxuation to the period of variability as seen in Figure 4. The shorter-period RR1 variables (lower left) generally have less variability compared to the longer-period RR0 variables (right). RR Lyraes with periods ranging from 0.2-0.4 are of the type RR1, and those with periods from 0.4-0.8 are of the type RR0. A summary of the numbers of each type of variable classified is shown in Table 1. The majority of our newly found variables were of the RR1 type. Given that RR1's have a lower amplitude of pulsation, it is reasonable to assume that many of these would not have been found in previous photographic studies.

The shortest period of our detected variables (0.049 days) is that of an SX Phoenix star (V161). Because of the short term variability and a longer term trend from night to night, we found it difficult to combined the data over several night so in figure 6 we only show the phased light curve for a single night(with about 6 cycles per night) to eliminate longer term variations.

TABLE 2
Variables Found in M14

V#	RA (h,m,s)			Dec (°,′,″)			Period (d)	Type
1	17	37	37.22	-3	13	59.4	∼20	lp
2	17	37	28.39	-3	16	44.7	2.7939	W Vir
3	17	37	35.87	-3	16	14.8	0.5223	RR0
4	17	37	46.87	-3	13	32.9	0.6514	RR0
5	17	37	27.02	-3	13	16.5	0.5488	RR0
6	17	37	38.37	-3	16	3.0	>25	lp
7	17	37	40.25	-3	16	22.0	13.361	lp
8	17	37	42.47	-3	14	10.2	0.6860	RR0
9	17	37	46.21	-3	15	25.1	0.5387	RR0
10	17	37	32.77	-3	18	9.9	0.5860	RR0
11	17	37	49.14	-3	18	28.5	0.6044	RR0
12	17	37	51.11	-3	17	43.1	0.5045	RR0
13	17	37	34.21	-3	16	44.2	0.5340	RR0
14	17	37	39.63	-3	14	48.5	0.4722	RR0
15	17	37	27.14	-3	12	17.7	0.5578	RR0
16	17	37	30.83	-3	15	21.3	0.6005	RR0
17	17	37	20.90	-3	12	42.8	∼11	lp
18	17	37	40.28	-3	15	7.7	0.4790	RR0
19	17	37	27.59	-3	14	43.3	0.5460	RR0
20	17	37	26.40	-3	13	7.1	0.2635	RR1
21	17	37	40.87	-3	12	40.3	0.3188	RR1
22	17	37	40.78	-3	13	11.0	0.6564	RR0
23	17	37	41.31	-3	16	4.2	>25	lp
24	17	37	35.97	-3	13	30.4	0.5199	RR0
29	17	37	31.61	-3	17	15.9	>25	lp
30	17	37	41.13	-3	14	57.7	0.5345	RR0
31	17	37	33.46	-3	14	13.7	0.6196	RR0
32	17	37	38.42	-3	12	18.7	0.6559	RR0
33	17	37	26.83	-3	14	31.1	0.4805	RR0
34	17	37	31.37	-3	14	18.6	0.6066	RR0
35	17	37	28.42	-3	15	34.8	0.5266	RR0
36	17	37	50.03	-3	20	28.4	0.6787	RR0
37	17	37	36.50	-3	14	27.1	0.4897	RR0
38	17	37	36.81	-3	15	2.7	0.5084	RR0
39	17	37	39.15	-3	14	46.1	0.5760	RR0
41	17	37	34.91	-3	14	47.1	0.2594	RR1
42	17	37	38.52	-3	14	33.5	0.6313	RR0
43	17	37	40.52	-3	14	23.4	0.5222	RR0
44	17	37	37.35	-3	12	47.6	0.2894	RR1
46	17	37	42.12	-3	15	50.7	0.3330	RR1
47	17	37	30.11	-3	14	18.1	0.8774	RR0
48	17	37	35.67	-3	14	4.7	0.4677	RR0
49	17	37	29.66	-3	15	3.8	0.6423	RR0
51	17	37	43.12	-3	19	52.2	0.2682	RR1
55	17	37	38.28	-3	12	58.8	0.3374	RR1
56	17	37	31.63	-3	17	48.8	0.3413	RR1
57	17	37	45.06	-3	16	40.9	0.5672	RR0
58	17	37	27.91	-3	15	18.5	0.4179	RR1
59	17	37	33.97	-3	14	15.9	0.5570	RR0
60	17	37	38.87	-3	13	50.6	0.5789	RR0
61	17	37	37.00	-3	15	28.6	0.5698	RR0
62	17	37	20.68	-3	17	19.4	0.6380	RR0
70	17	37	38.93	-3	15	8.1	0.6060	RR0
73	17	37	36.39	-3	14	38.1	>25	lp
74	17	37	36.54	-3	13	14.5	>25	lp
75	17	37	38.43	-3	14	55.7	0.5453	RR0
76	17	37	29.05	-3	14	44.1	1.8979	RR0
77	17	37	28.81	-3	13	46.5	0.7910	RR0
78	17	37	26.97	-3	14	47.4	0.3102	RR1
79	17	37	35.35	-3	15	00.3	0.5597	RR0
88	17	37	30.85	-3	14	32.4	0.3130	RR1
90	17	37	33.51	-3	15	16.2	0.3512	RR1
94	17	37	23.04	-3	14	50.5	0.2585	RR1

TABLE 2 — *Continued*

V#	RA (h,m,s)			Dec (°,′,″)			Period (d)	Type
95	17	37	24.17	-3	17	28.5	0.3596	RR1
96	17	37	24.72	-3	14	46.3	0.2524	RR1
97	17	37	25.02	-3	18	36.5	0.3774	EB
98	17	37	25.81	-3	12	47.8	0.2579	RR1
99	17	37	26.58	-3	14	46.1	∼15	lp
100	17	37	29.72	-3	15	20.5	0.2612	RR1
101	17	37	30.28	-3	15	52.7	>25	lp
102	17	37	31.38	-3	16	0.6	∼15	lp
103	17	37	32.48	-3	14	12.5	>25	lp
104	17	37	32.69	-3	14	56.0	0.2620	RR1
105	17	37	32.95	-3	14	3.3	0.2793	RR1
106	17	37	33.28	-3	14	46.4	0.5465	RR0
107	17	37	33.56	-3	14	48.2	0.2950	RR1
108	17	37	33.62	-3	15	12.0	0.3565	RR1
109	17	37	33.64	-3	14	40.9	0.6562	RR0
110	17	37	33.64	-3	16	10.2	0.3013	RR1
111	17	37	33.71	-3	15	11.9	0.2791	RR1
112	17	37	33.76	-3	17	14.7	0.3156	RR1
113	17	37	33.91	-3	14	27.5	0.2574	RR1
114	17	37	33.91	-3	14	52.5	0.3325	RR1
115	17	37	33.95	-3	14	24.1	0.3359	RR1
116	17	37	34.03	-3	15	37.7	0.2521	RR1
117	17	37	34.10	-3	14	35.9	0.3394	RR1
118	17	37	34.24	-3	16	13.0	0.3803	RR1
119	17	37	34.45	-3	14	52.1	0.3341	RR1
120	17	37	34.65	-3	13	29.6	0.3279	RR1
121	17	37	35.04	-3	15	19.7	0.2704	RR1
122	17	37	35.30	-3	14	39.2	0.5590	RR0
123	17	37	35.55	-3	15	44.1	0.2846	RR1
124	17	37	35.75	-3	15	27.3	0.2762	RR0
125	17	37	35.79	-3	15	15.1	∼20	lp
126	17	37	35.83	-3	14	53.7	0.2939	RR1
127	17	37	35.92	-3	14	32.8	0.2983	RR1
128	17	37	35.95	-3	13	52.8	0.3935	RR1
129	17	37	36.11	-3	15	1.4	0.2796	RR1
130	17	37	36.26	-3	15	25.4	0.5961	RR0
131	17	37	36.27	-3	14	54.3	0.2697	RR1
132	17	37	36.53	-3	15	14.7	0.4822	RR0
133	17	37	36.64	-3	18	15.9	0.3030	RR1
134	17	37	36.69	-3	15	5.8	0.5072	RR0
135	17	37	36.82	-3	13	41.9	0.3382	RR1
136	17	37	36.83	-3	15	24.5	0.3305	RR1
137	17	37	37.48	-3	14	40.7	0.2763	RR1
138	17	37	37.93	-3	15	33.0	0.3710	RR1
139	17	37	37.99	-3	17	23.7	0.2722	RR1
140	17	37	38.21	-3	15	51.9	0.7609	RR0
141	17	37	38.31	-3	14	27.2	0.6433	RR0
142	17	37	38.72	-3	14	2.1	0.4618	RR0
143	17	37	38.82	-3	16	31.2	0.3185	RR1
144	17	37	39.27	-3	14	29.7	0.3758	RR1
145	17	37	39.97	-3	15	1.4	0.3003	RR1
146	17	37	40.16	-3	16	8.6	>25	lp
147	17	37	40.22	-3	15	55.5	0.4932	RR0
148	17	37	40.73	-3	17	0.3	0.2651	RR1
149	17	37	41.07	-3	10	4.7	0.5523	RR0
150	17	37	41.14	-3	14	8.0	0.8028	RR0
151	17	37	41.19	-3	14	22.7	0.3198	RR1
152	17	37	41.90	-3	15	37.1	>25	lp
153	17	37	41.98	-3	11	56.0	0.2650	RR1
154	17	37	42.54	-3	13	59.4	0.2551	RR1
155	17	37	42.93	-3	14	5.3	∼15	lp
156	17	37	43.60	-3	14	24.6	>25	lp
157	17	37	43.79	-3	16	13.4	0.2626	RR1
158	17	37	43.88	-3	13	0.7	0.7242	RR0
159	17	37	43.99	-3	13	44.8	0.2897	RR1
160	17	37	44.24	-3	15	34.8	0.3400	RR1
161	17	37	44.52	-3	11	51.5	0.0490	SX Phe
162	17	37	49.69	-3	11	49.2	∼20	lp
163	17	37	53.71	-3	14	18.8	0.2903	RR1
164	17	37	56.28	-3	10	16.3	0.3326	RR1

We assign 'lp' to any variable with a period greater than 3 days.

Several of the RR0 variables showed evidence of the Blazhko effect (Blazhko 1907; Smith 2004) resulting in long term modulation in the amplitude. Although our observations were not long enough to find this secondary

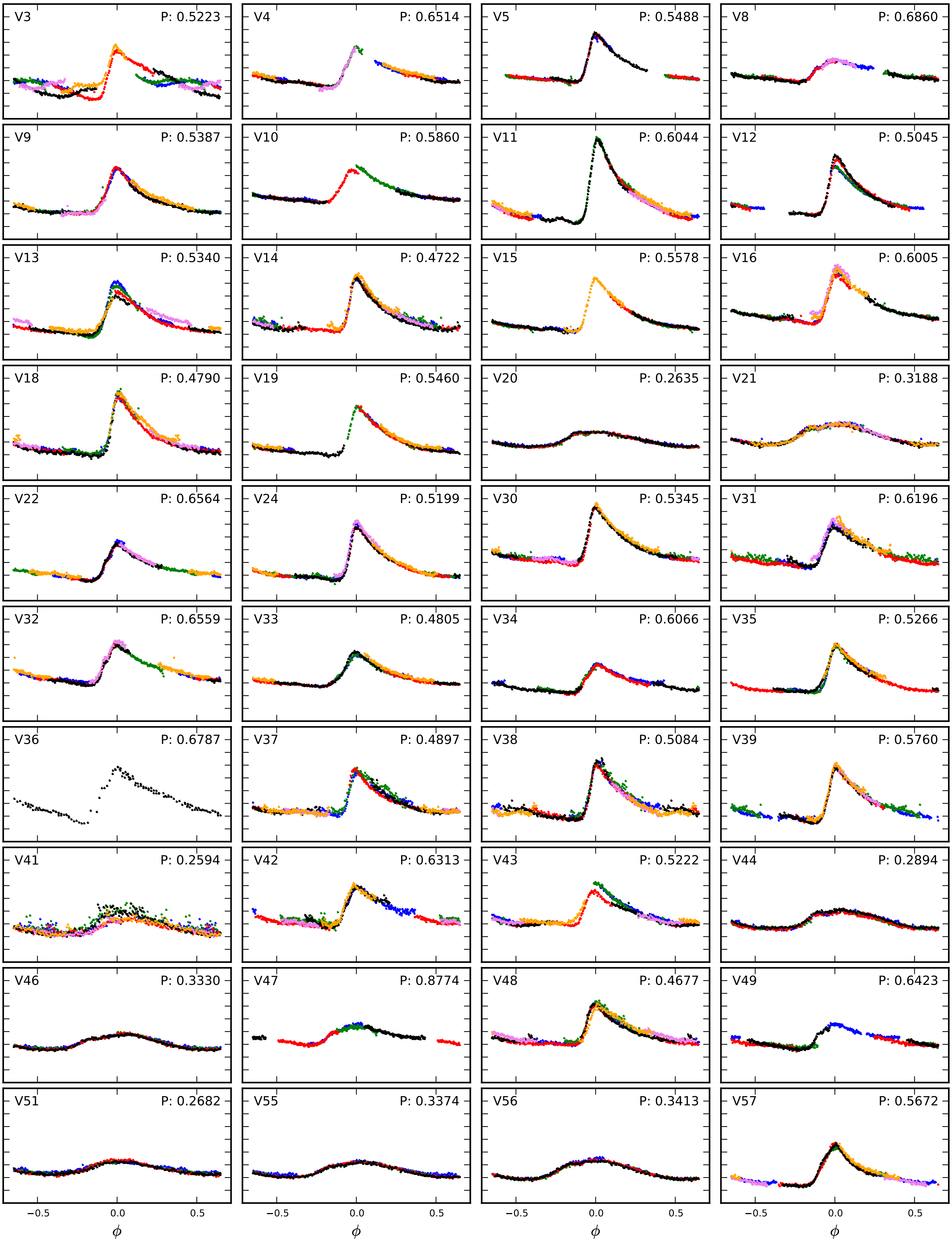

FIG. 6.— Phased light curves for all detected variables with periods under 3 days. The vast majority of these variables are RR Lyarae stars.

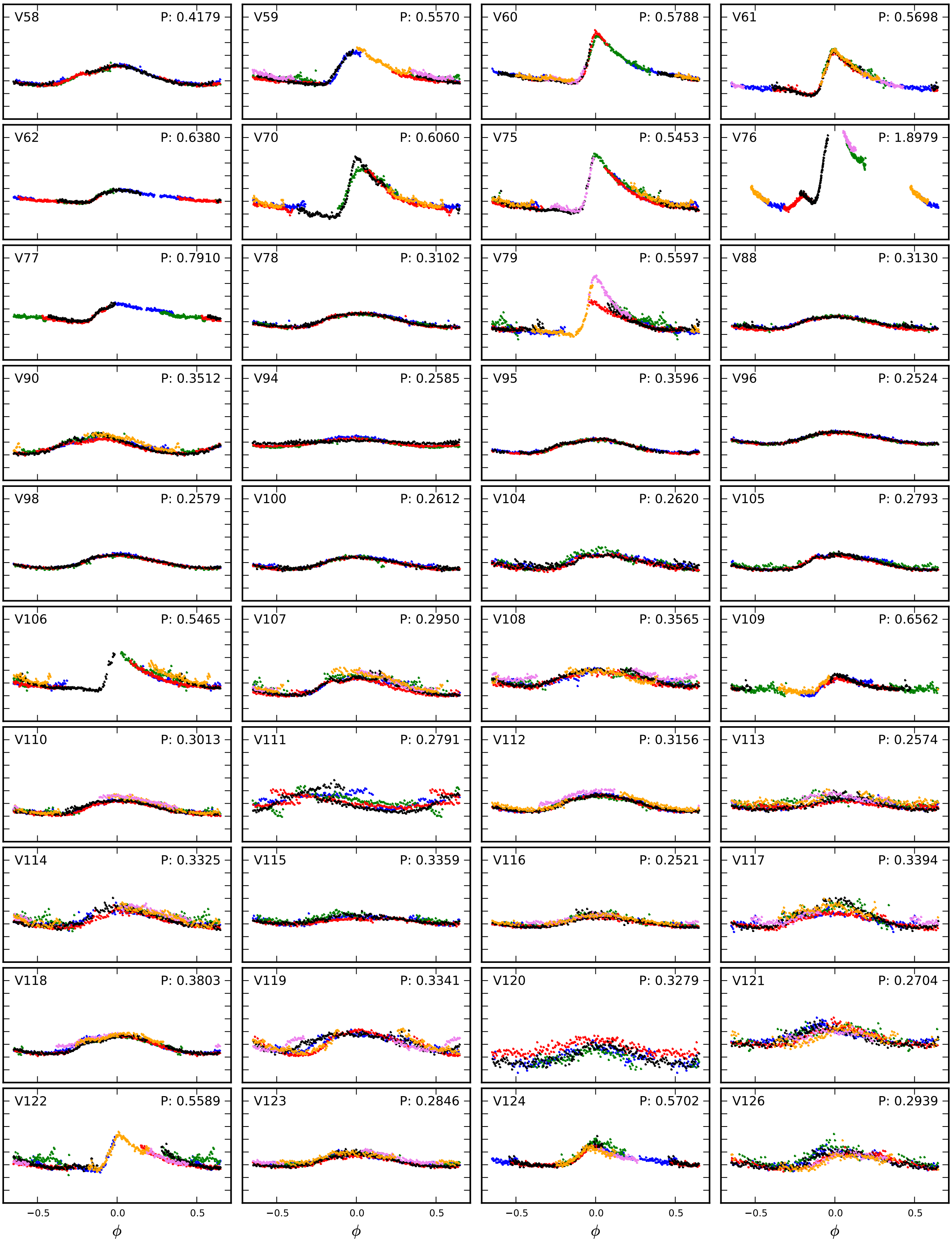

FIG. 6.— (Continued) Phased light curves for all detected variables with periods under 3 days. The vast majority of these variables are RR Lyrae stars.

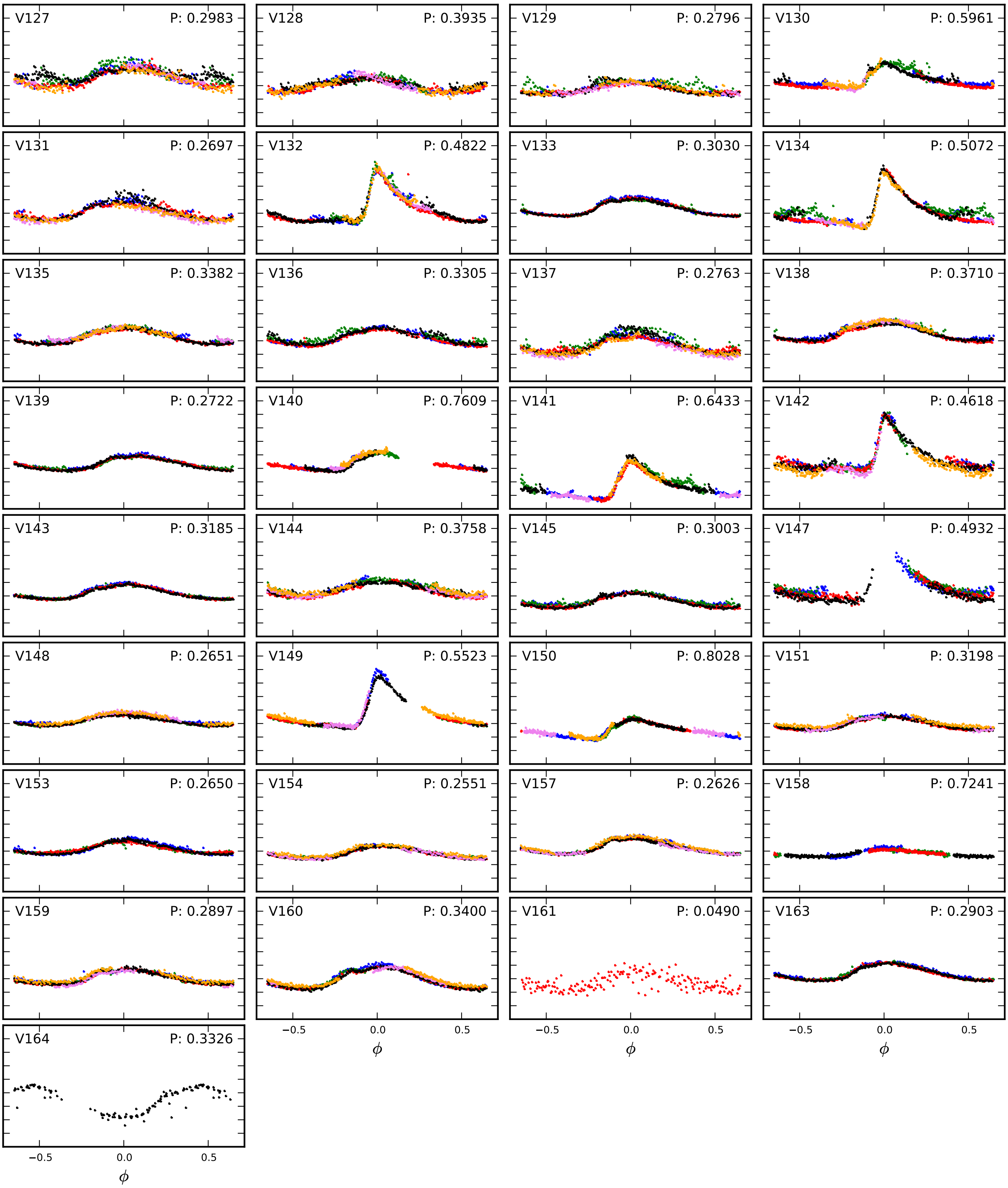

FIG. 6.— (Continued) Phased light curves for all detected variables with periods under 3 days. The vast majority of these variables are RR Lyrae stars.

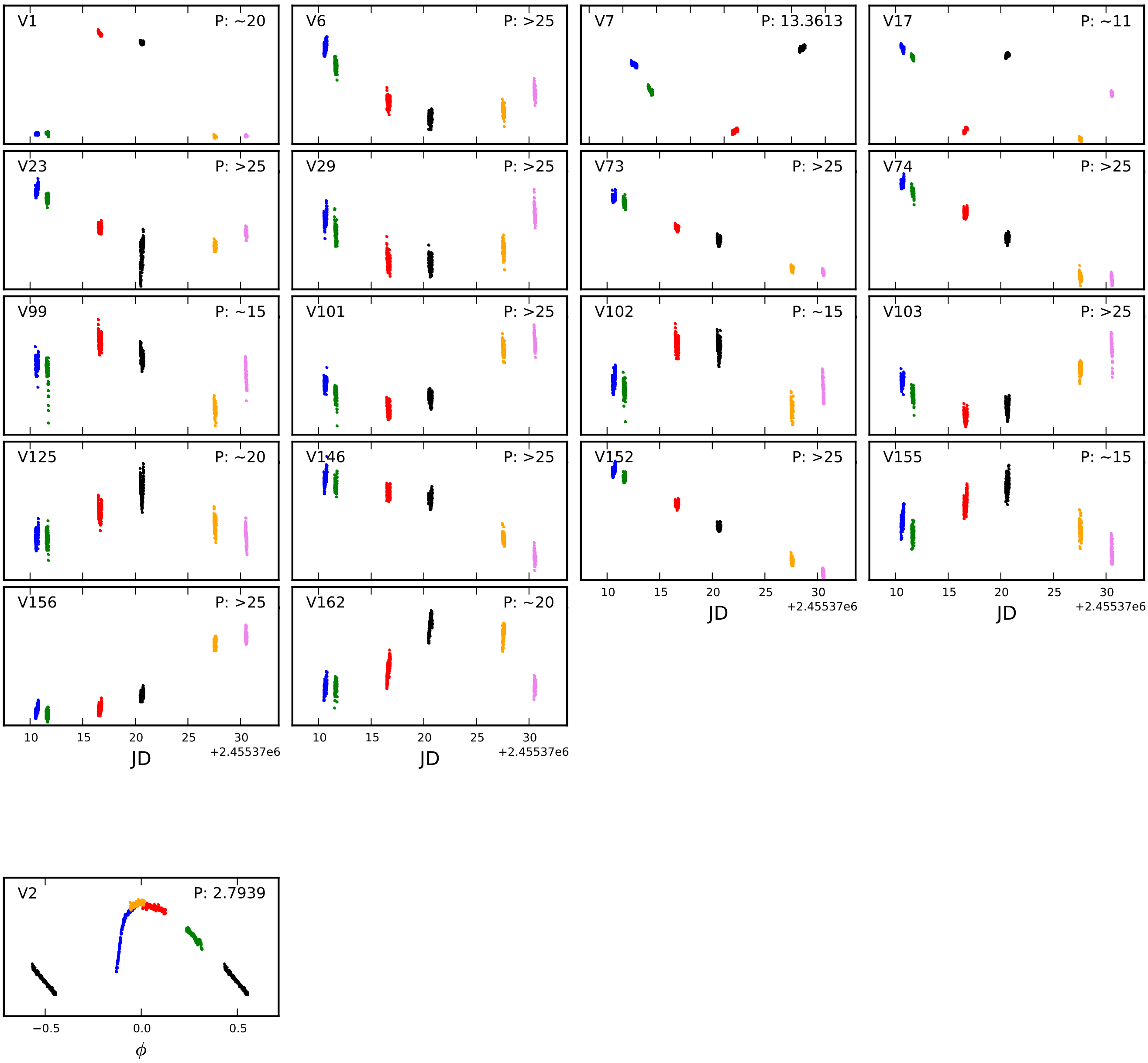

FIG. 7.— Light curves for all detected variables with periods over 3 days.

period, the effect is apparent in V3, V13, V31, V43, V70, and V79 (Figure 4.3).

Among the new variables we detected was an eclipsing binary shown in Figure 5, V97. The shape of the light curve indicates it is a W UMa contact binary. The distortion between and similar depths of the eclipses suggest an overcontact binary, while the relative flatness of eclipses suggest a large mass ratio (Rucinski 1992; Webbink 2003).

By running all of our Cerro Tololo data through ISIS simultaneously we were able to detect several possible long term variables. Many of these are most likely red giant stars undergoing longer term pulsations. All of our potential longer period variables are included in Table 2 listed as 'lp' and their light curves are plotted unphased in Figure 4.3. Our observing time span was not long enough to observe multiple cycles for these variables. Those with periods listed are only estimates.

All detected variables and their periods and classification are shown in Table 2. Light curves of variables with shorter periods are shown phased in Figure 6, whereas the light curves of longer period variables are shown unphased except for V2 in Figure 7. V2 is an W Vir star with a period of 2.7939 days. Given its relatively short period, we show its light curve as phased.

5. CONCLUSIONS

We observed the globular star cluster M14 for 12 nights over a 40 day period using the SARA telescopes located at KPNO and CTIO. We used the image subtraction method of Alard (2000) to search for variable stars in M14. We confirmed 63 previously known variables cataloagued by Wehlau & Froelich (1994). In addition to the previoulsy known variables we have identified 71 new variables. Of the variables we were able to detect we have confirmed the periods the Wehlau and Froelich RR Lyrae stars with one exception. Of the total number of confirmed variables we found 55 RR0, 57 RR1, 19 variables with periods greater than 2 days, a W UMa contact binary, and an SX Phoenix star. We confirmed the periods of previously found variables as well as the determined of the periods, classification, and light curves of the newly discovered variables.

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