# The Clusters AgeS Experiment (CASE).
# Variable Stars in the Field of the Globular Cluster NGC 6362[*]

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### ABSTRACT

The field of the globular cluster NGC 6362 was monitored between 1995 and 2009 in a search for variable stars. *BV* light curves were obtained for 69 periodic variable stars including 34 known RR Lyr stars, 10 known objects of other types and 25 newly detected variable stars. Among the latter we identified 18 proper-motion members of the cluster: seven detached eclipsing binaries (DEBs), six SX Phe stars, two W UMa binaries, two spotted red giants, and a very interesting eclipsing binary composed of two red giants – the first example of such a system found in a globular cluster. Five of the DEBs are located at the turnoff region, and the remaining two are redward of the lower main sequence. Eighty-four objects from the central $9 \times 9$ arcmin$^2$ of the cluster were found in the region of cluster blue stragglers. Of these 70 are proper motion (PM) members of NGC 6362 (including all SX Phe and two W UMa stars), and five are field stars. The remaining nine objects lacking PM information are located at the very core of the cluster, and as such they are likely genuine blue stragglers.

**Key words:** *globular clusters: individual (NGC 6362) – Stars: variables: general – blue stragglers – binaries: eclipsing*

## 1. Introduction

NGC 6362 is a nearby ($(m-M)_V = 14.68$ mag) globular cluster located at a rather high Galactic latitude ($b = -17°\!.6$) in a field of low reddening with $E(B-V) = 0.09$ mag (Harris 1996, 2010 edition). These properties together with a low concentration make it an attractive target for detailed studies with ground based telescopes. The photometric survey presented here is a part of the CASE project (Kaluzny *et al.* 2005) conducted with telescopes of the Las Campanas Observatory.

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[*]Based on data obtained with du Pont and Swope telescopes at Las Campanas Observatory.

Early pre-CCD searches for variable stars in the cluster were summarized by Clement *et al.* (2001). They resulted in the detection of 31 RR Lyr stars. Based on CCD-data, Mazur *et al.* (1999) found 19 new variable stars (among them five RR Lyr stars, four SX Phe stars and eight eclipsing binaries). Periods were established only for short period variables with $P < 1$ d. Subsequently, Olech *et al.* (2001) performed an analysis of light curves for 35 RR Lyr stars from the cluster. Three of these turned out to be non-radial pulsators.

In this contribution we present results of an extended survey conducted at Las Campanas Observatory between 1995 and 2009. Section 2 contains a report on the observations and explains the methods used to calibrate the photometry. The detected variable stars are presented and discussed in Section 3. The paper is summarized in Section 4.

## 2.  Observations

This paper is based on two sets of images collected at Las Campanas Observatory. The first was obtained using the 2.5-m du Pont telescope and the $2048 \times 2048$ TEK5 CCD camera with a field of view of $8\overset{'}{.}84$ on a side at a scale of 0.259 arcsec/pixel. Observations were conducted on 45 nights from April 21, 1995 to September 26, 2009, always with the same set of filters. For the analysis, we used 1748 *V*-images with seeing ranging from $0\overset{''}{.}79$ to $2\overset{''}{.}48$, and 334 *B*-images with seeing ranging from $0\overset{''}{.}86$ to $2\overset{''}{.}15$. The median value of the seeing was $1\overset{''}{.}32$ and $1\overset{''}{.}38$ for *V* and *B*, respectively. The second set of images was obtained with the 1.0-m Swope telescope and the $2048 \times 3150$ SITE3 CCD camera. The field of view was $14.8 \times 22.8$ arcmin$^2$ at a scale of 0.435 arcsec/pixel. About 30% of the images were taken with a subraster providing a field of view of $14.8 \times 14.8$ arcmin$^2$. Observations were conducted on 103 nights from July 8, 1999 to September 9, 2009. The same filters were used for all observations. For the analysis, we used 3200 *V*-images with seeing ranging from $0\overset{''}{.}80$ to $2\overset{''}{.}25$ and 558 *B*-images with seeing ranging from $0\overset{''}{.}94$ to $2\overset{''}{.}17$. The median value of the seeing was $1\overset{''}{.}49$ and $1\overset{''}{.}55$ for *V* and *B*, respectively.

The photometry was measured using the image subtraction technique. For the du Pont data we used a modified version of the ISIS V2.1 package (Allard 2000). For the images collected with the Swope telescope the DIAPL package[†] was used. For each set and each filter, a reference image was constructed by combining several high quality frames. DAOPHOT, ALLSTAR and DAOGROW codes (Stetson 1987, 1990) were used to extract the profile photometry, and to derive aperture corrections for the reference images. We also extracted profile photometry for individual images from the du Pont telescope. This allowed us to obtain useful measurements for stars whose profiles were overexposed on the reference images. Moreover, this profile photometry enabled an unambiguous identification
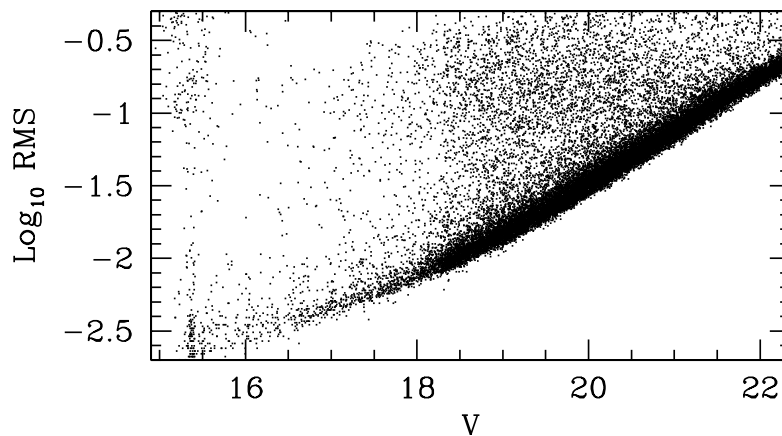
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[†]*http://users.camk.edu.pl/pych/DIAPL/index.html*

Fig. 1. Standard deviation *vs.* average *V* magnitude for light curves of stars from the NGC 6362 field. Light curves are based on images from the du Pont telescope.

of variable stars in crowded fields, which is sometimes problematic when image subtraction only is used. We used a list of stars based on du Pont photometry when reducing the Swope data for the central part of the cluster. The better spatial resolution of du Pont images allowed us to resolve numerous blends on images obtained with the smaller telescope. The accuracy of the du Pont photometry is illustrated in Fig. 1, in which the standard deviation of the photometric measurements is plotted as a function of the average magnitude in *V*.

### 2.1.  *Calibration*

The photometry collected with du Pont telescope was transformed to the standard *BV* system based on observations of stars from Landolt fields (Landolt 1992). On the night of May 3, 2001 we observed 19 stars from four such fields, each of them observed twice. These data were used to find the coefficients of linear transformation from the instrumental system to the standard one. Residual differences between the standard and recovered magnitudes and colors amounted to 0.009 mag, 0.008 mag and 0.010 mag for *V*, *B* and $B-V$, respectively. The residuals did not show any systematic dependence on the color index. Transformations for photometry obtained with the Swope telescope were based on the calibrated data from du Pont telescope. The linear transformations proved to be entirely adequate. Fig. 2 shows the color–magnitude diagram (CMD) of the observed fields (RR Lyr stars are not shown). This figure shows in particular the wide range of stellar population examined for variability. Clearly visible, especially in the left panel, is a rich group of blue stragglers. The relative contamination of the cluster by field interlopers increases with the increasing field of view. Fig. 2 is based on reference images. Stars with large formal errors in *V* and $B-V$ or those at large distances from the cluster center are not shown. Full sets of photometry can be downloaded from the CASE archive.[‡].

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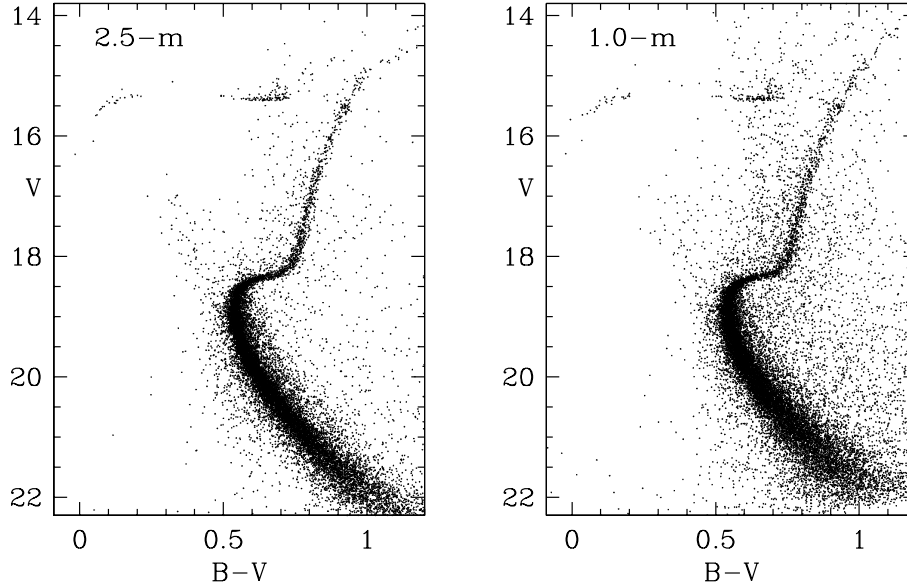[‡]*http://case.camk.edu.pl/*

Fig. 2. CMDs for NGC 6362 based on the data from the du Pont telescope (*left*) and Swope telescope (*right*).

### 2.2.    *Search for Variable Stars*

The search for variable stars was conducted using AOV and AOVTRANS algorithms implemented in the TATRY code (Schwarzenberg-Czerny 1996, Schwarzenberg-Czerny and Beaulieu 2006). We examined the du Pont light curves of 13299 stars with $V < 22.0$ mag and the Swope light curves of 18754 stars with $V < 20.75$ mag. The limits of detectable variability depended on the accuracy of photometric measurements, which for the du Pont data decreased from 3 mmag at $V = 16$ mag to 30 mmag at $V = 20$ mag and 100 mmag at $V = 22$ mag (Fig. 1). For the Swope data it decreased from 3.5 mmag at $V = 15$ mag through 32 mmag at $V = 19.25$  mag to 100 mmag at $V = 20.75$ mag.

### 3.    Variable Stars

We detected a total of 69 certain variable stars of which 48 have photometry from both telescopes. Among these were 34 known RR Lyr stars, whose light curves will be analyzed in a separate paper (Moskalik *et al.*, in preparation). The basic properties of the remaining variable stars are listed in Table 1 together with their equatorial coordinates. The coordinates are given in the UCAC4 system (Zacharias *et al.* 2013) and are accurate to about $0.''2$. Variables V53–V77 are new detections. Their finding charts are presented in Fig. 3.

The *V* magnitudes listed in Table 1 correspond to the maximum light in the case of eclipsing binaries, while for the remaining variables average magnitudes are provided. For each variable the $B - V$ color is given, followed by the amplitude in the
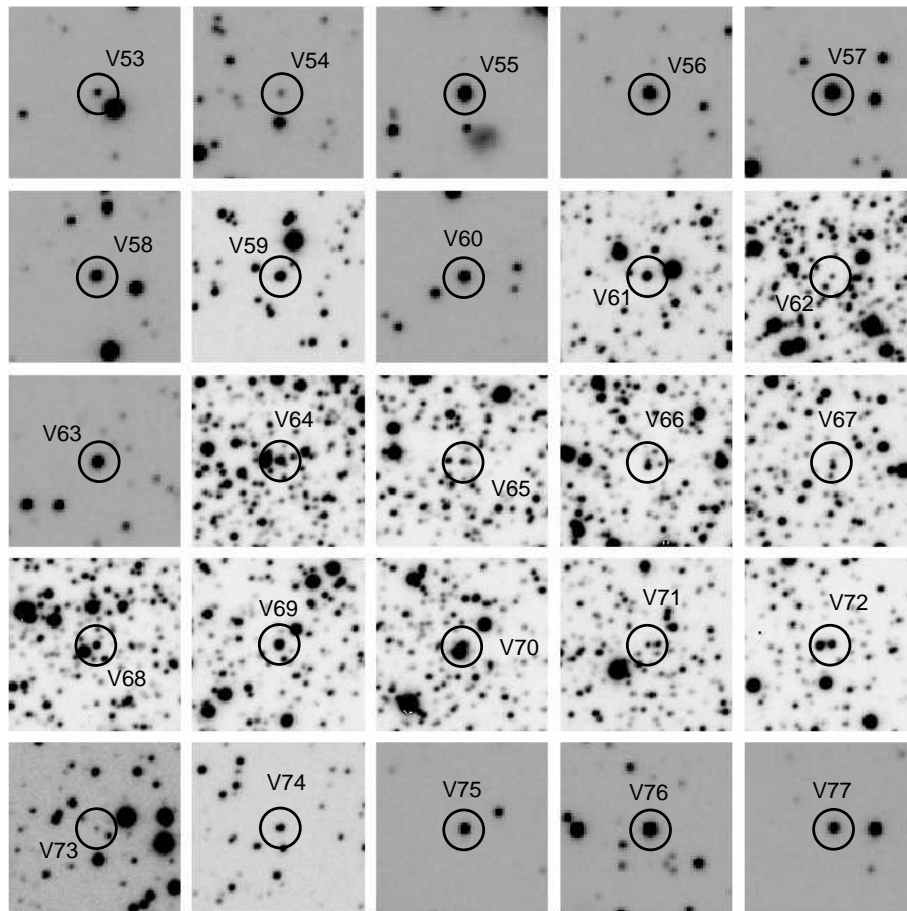
Fig. 3. Finding charts for the newly detected variable stars V53–77. Each chart is 30″ on a side; North is up and East to the left.

*V*-band. Periods of variability were found for all stars. However, the light curves of some objects classified as "spotted" are not coherent and show phase shifts from season to season. In such cases, we give periods obtained for the indicated season(s). The last column of Table 1 gives the membership status based on proper motions taken from Zloczewski *et al.* (2012) and Narloch *et al.* (in preparation). Phased light curves of the variable stars from Table 1, ordered according to the type of variability, are presented in Figs. 4–6.

A CMD of the cluster with the locations of the variable stars is shown in Fig. 5. This CMD is based on the du Pont photometry and includes only stars selected by Zloczewski *et al.* (2012) as proper motion members of NGC 6362. Variable stars which, based on their proper motions, likely belong to the cluster, are marked in red; the remaining ones – in blue. The location of each variable coincides with the center of the corresponding label.
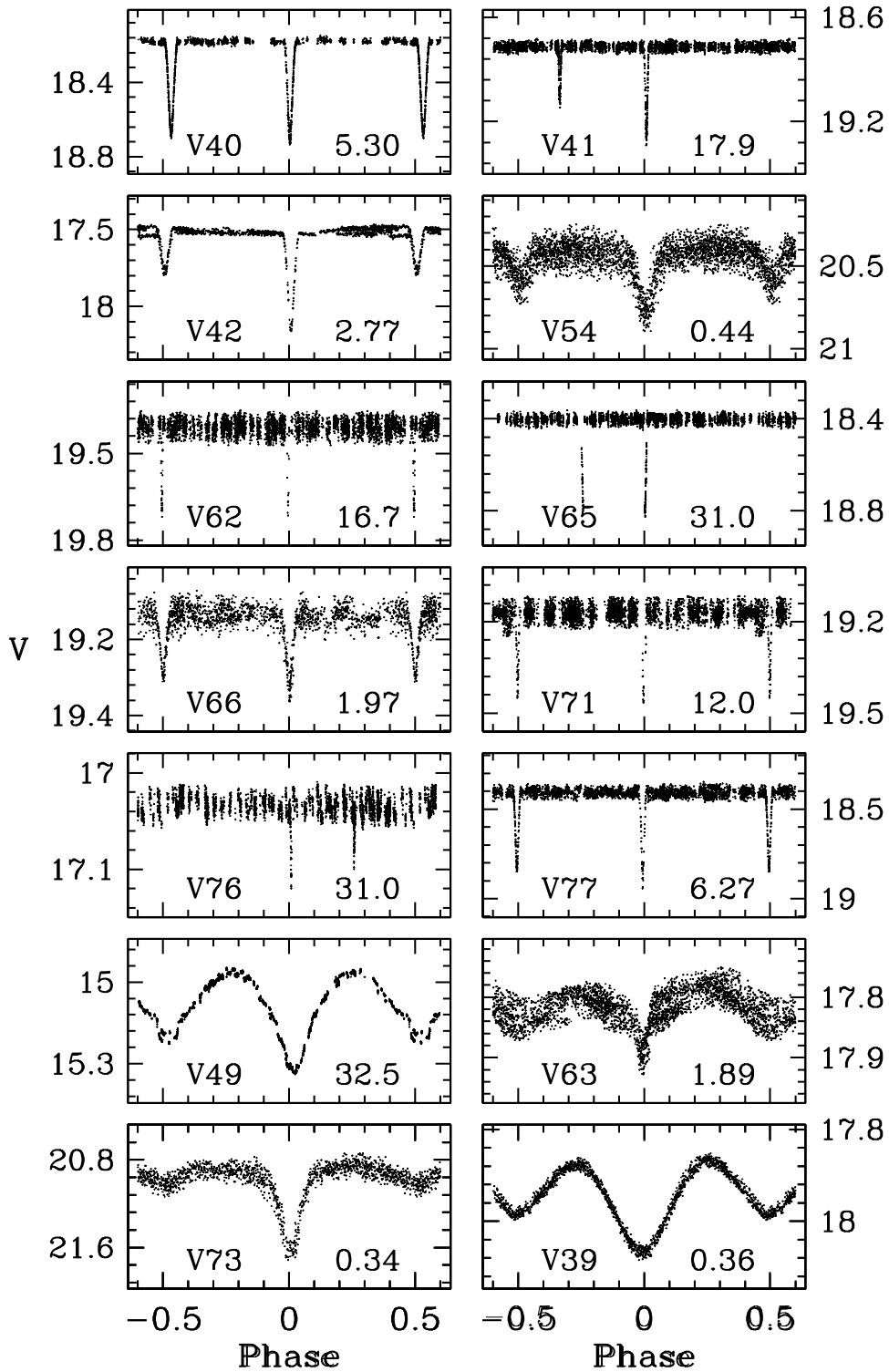
Fig. 4. Phased *V* curves of variable stars detected in the field of NGC 6362. Inserted labels give star ID and period in days.
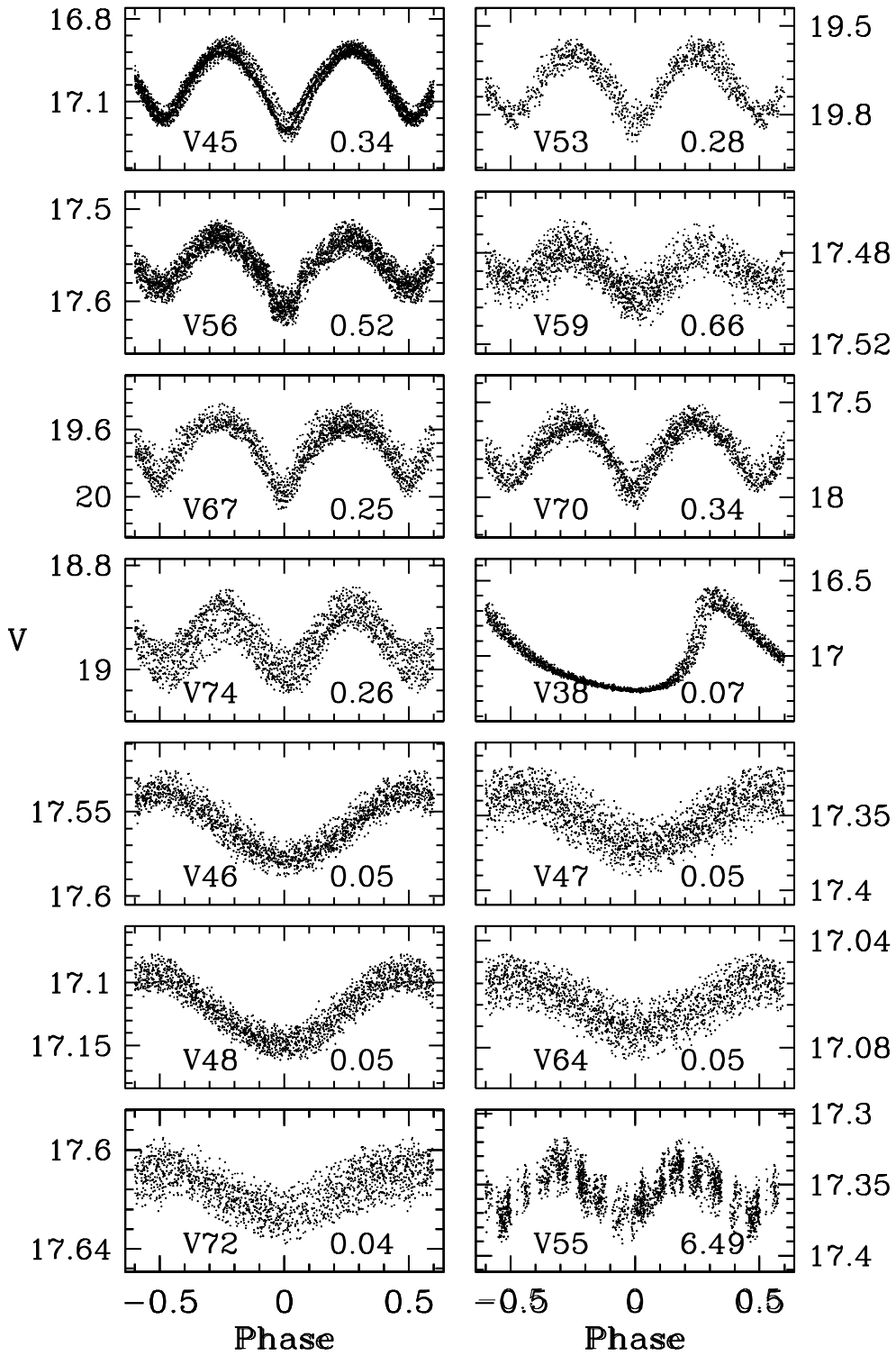
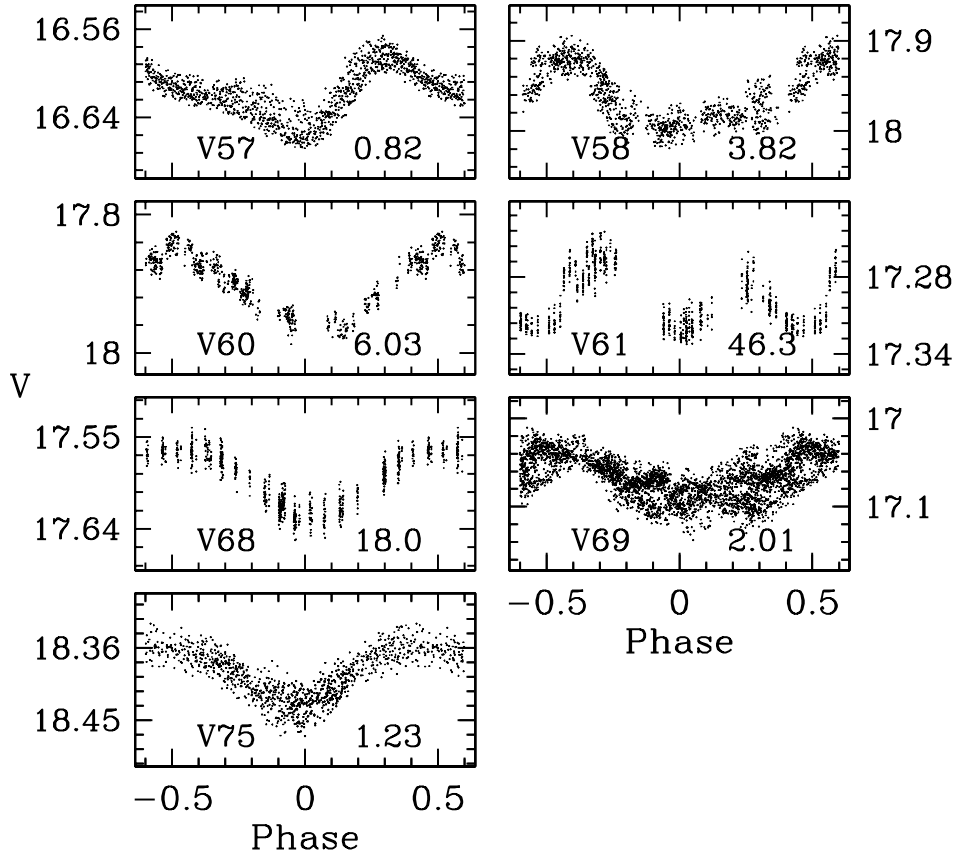Fig. 5. Same as Fig. 4. The V55 curve shows data from seasons 1999–2003.

Fig. 6. Same as Fig. 4. Curves of V57, V58 and V75 show data from the 2001 season; curves of V60, V61 and V68 show data from the 1999 season.

### 3.1.  *Eclipsing Binaries*

We detected a total of 12 detached eclipsing binaries. Of these, seven are proper motion members of the cluster. Binaries V40, V41 V62, V65 and V71 are located at the cluster turnoff region. Their orbital periods range from 5.2 d for V40 to 17.9 d for V41. These systems are potentially interesting targets for a detailed follow up study aiming at the determination of their absolute parameters, and the age and distance of the cluster. We are presently conducting such an analysis for V40 and V41 (Kaluzny *et al.*, in preparation). The variability of these two systems was first reported by Mazur *et al.* (1999). Based on the present photometry, we determined precise ephemerides and obtained complete light curves for both binaries. It is remarkable that V40 has an eccentric orbit despite a relatively short period. At an age of about 12 Gyr (Harris 1996, 2010 edition), its orbit should have been fully circularized by the tidal friction mechanism (Mazeh 2008, Mathieu *et al.* 2004). There is no evidence for the presence of a third body in this system. We speculate that the orbit of V40 was distorted during the last few Gyr as the result of a close encounter.

Table 1

Basic data of NGC 6362 variable stars identified within the present survey

| ID | RA | DEC | $V$ [mag] | $B-V$ [mag] | $A_V$ [mag] | Period [d] | Type[c] | Mem |
|----|-----|------|-----------|-------------|-------------|------------|---------|-----|
| V38 | 262.93172 | −67.04958 | 17.02 | 0.28 | 0.63 | 0.06661582(1) | SX,BS | Y |
| V39 | 263.03523 | −67.05412 | 17.86 | 0.39 | 0.20 | 0.3632599(1) | EW,BS | Y |
| V40 | 263.01702 | −67.06264 | 18.22 | 0.55 | 0.54 | 5.2961749(1) | EA | Y |
| V41 | 262.89739 | −67.06754 | 18.77 | 0.57 | 0.58 | 17.888844(4) | EA | Y |
| V42 | 262.88250 | −67.01098 | 17.51 | 0.69 | 0.64 | 2.769390(6) | EA | N |
| V45 | 262.83317 | −67.05624 | 16.92 | 0.80 | 0.33 | 0.3407063(1) | EW | N |
| V46 | 263.10395 | −67.00871 | 17.55 | 0.30 | 0.05 | 0.050634688(5) | SX,BS | Y |
| V47 | 263.05427 | −67.04386 | 17.35 | 0.29 | 0.05 | 0.052234111(5) | SX,BS | Y |
| V48 | 262.99927 | −67.06386 | 17.12 | 0.33 | 0.06 | 0.047920021(5) | SX,BS | Y |
| V49 | 263.00796 | −67.07682 | 14.97 | 0.93 | 0.36 | 32.504(1) | EB,RG | Y |
| V53 | 263.15424 | −67.00576 | 19.61 | 0.79 | 0.25 | 0.2826720(1) | EW | N |
| V54 | 263.22510 | −67.09877 | 20.41 | 0.86 | 0.48 | 0.4430415(2) | EA | Y |
| V55 | 263.13284 | −67.02132 | 17.35 | 0.57 | 0.05 | 6.49353(5) | Ell | N |
| V56 | 263.13213 | −67.03085 | 17.50 | 0.23 | 0.09 | 0.5193450(3) | EW | N |
| V57 | 263.12126 | −67.01887 | 16.62 | 0.99 | 0.08 | 0.81848(1)[a] | Sp? | N |
| V58 | 263.11699 | −67.14543 | 17.96 | 0.95 | 0.09 | 3.815(1)[a] | Sp | N |
| V59 | 263.10289 | −67.11148 | 17.48 | 0.31 | 0.03 | 0.6601102(4) | EW/Ell,BS | Y |
| V60 | 263.05838 | −67.01875 | 17.89 | 0.92 | 0.12 | 6.0255(5)[b] | Sp | N |
| V61 | 263.07557 | −67.06092 | 17.23 | 0.83 | 0.07 | 46.35(1)[b] | Sp,RG | Y |
| V62 | 263.02428 | −67.05223 | 19.39 | 0.55 | 0.33 | 16.73212(6) | EA | Y |
| V63 | 263.01446 | −67.13954 | 17.80 | 0.48 | 0.15 | 1.890156(3) | EB | N |
| V64 | 262.99266 | −67.06273 | 17.06 | 0.31 | 0.03 | 0.050162402(5) | SX,BS | Y |
| V65 | 262.94883 | −67.06480 | 18.39 | 0.55 | 0.43 | 30.9723(1) | EA | Y |
| V66 | 262.95013 | −67.03277 | 19.13 | 0.71 | 0.20 | 1.974206(4) | EA | Y |
| V67 | 262.93970 | −67.07393 | 19.55 | 0.72 | 0.52 | 0.25080101(6) | EW | N |
| V68 | 262.93710 | −67.05581 | 17.62 | 0.77 | 0.08 | 17.98(1)[b] | Sp,RG | Y |
| V69 | 262.93217 | −67.02965 | 17.14 | 1.08 | 0.08 | 2.0125(1) | Sp | N |
| V70 | 262.91209 | −67.04824 | 17.60 | 0.49 | 0.47 | 0.3393452(3) | EW | N |
| V71 | 262.90240 | −67.03735 | 19.17 | 0.56 | 0.30 | 11.965385(5) | EA | Y |
| V72 | 262.87070 | −67.04273 | 17.61 | 0.29 | 0.03 | 0.0436729(1) | SX,BS | Y |
| V73 | 262.82041 | −67.06011 | 20.86 | 1.11 | 0.82 | 0.338903(5) | EB | N |
| V74 | 262.82326 | −66.99927 | 18.82 | 0.76 | 0.17 | 0.261080(3) | EW | N |
| V75 | 262.88797 | −67.02960 | 18.40 | 1.11 | 0.10 | 1.2290(2)[a] | Sp | N |
| V76 | 262.76813 | −67.05666 | 17.04 | 0.74 | 0.09 | 30.96345(5) | EA | N |
| V77 | 262.86987 | −67.03463 | 18.41 | 0.89 | 0.52 | 6.2746(1) | EA | − |

[a]for the 2001 season. [b]for the 1999 season. [c]Types: EW – contact binary, EB – close eclipsing binary, EA – detached eclipsing binary, SX – SX Phe star, Sp – spotted variable, BS – blue straggler, Ell – ellipsoidal variable, RG – red giant. For V38–V49, which were described by Mazur *et al.* (1999), updated parameters are provided. V53–V77 are new detections.

 

The light curve of V62 shows two partial eclipses of similar depth. As a result the photometric solution is likely to be degenerate, allowing for a broad range of relative radii. Such a degeneracy may be overcome by the determination of the light ratio from spectra. However, this approach would be problematic given the
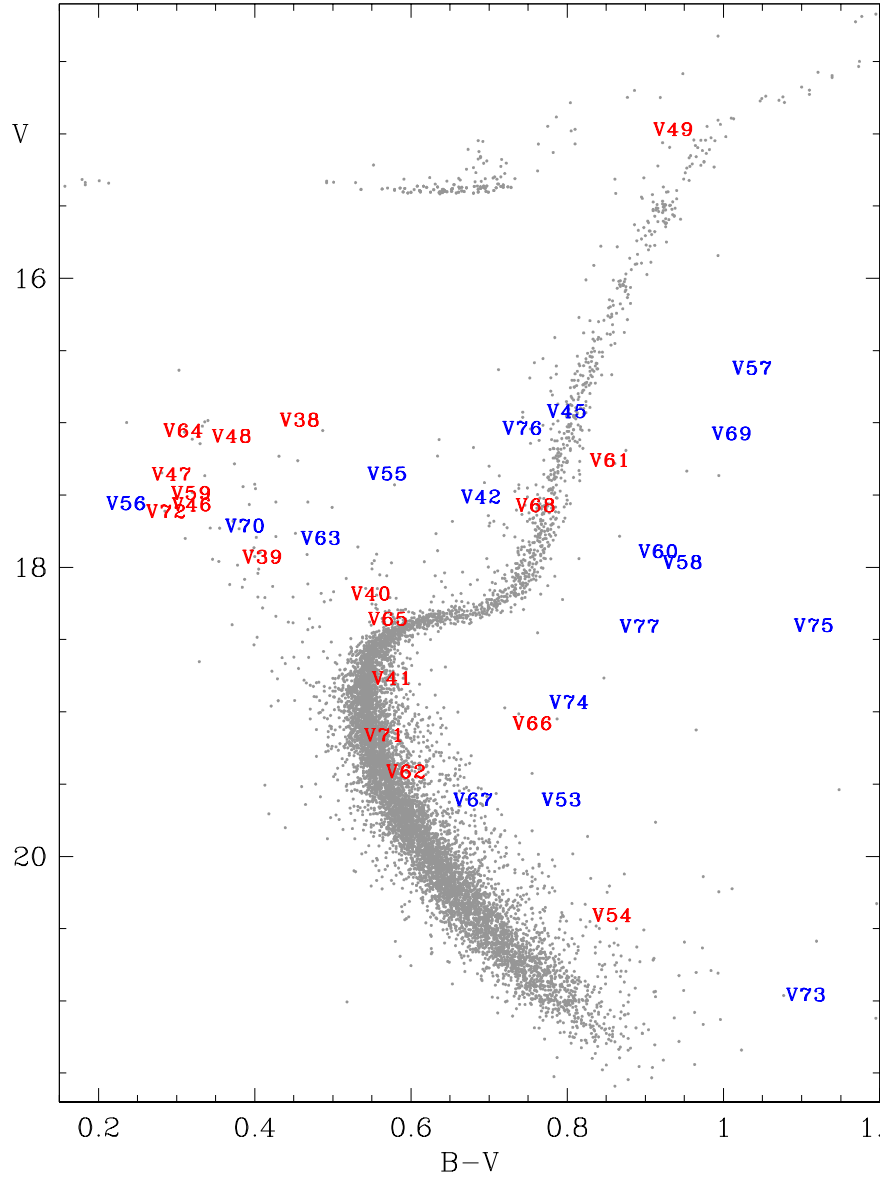
Fig. 7. CMD for NGC 6362. Points are PM members of the cluster. Variable stars being PM members are marked in red; the remaining ones – in blue. The location of each variable coincides with the center of the corresponding label. The CMD is truncated at $V = 21.7$ mag due to the lack of PM information for fainter stars.

faintness of the system. Similar comments apply to V71. Much more promising in this respect is the binary V65. Our phased light curve of this system shows one eclipse with a depth of 0.45 mag. We did not cover the bottom of the second eclipse, but the data suggest that both eclipses are close to totality. If this is the case then the analysis of full light curves would be straightforward.
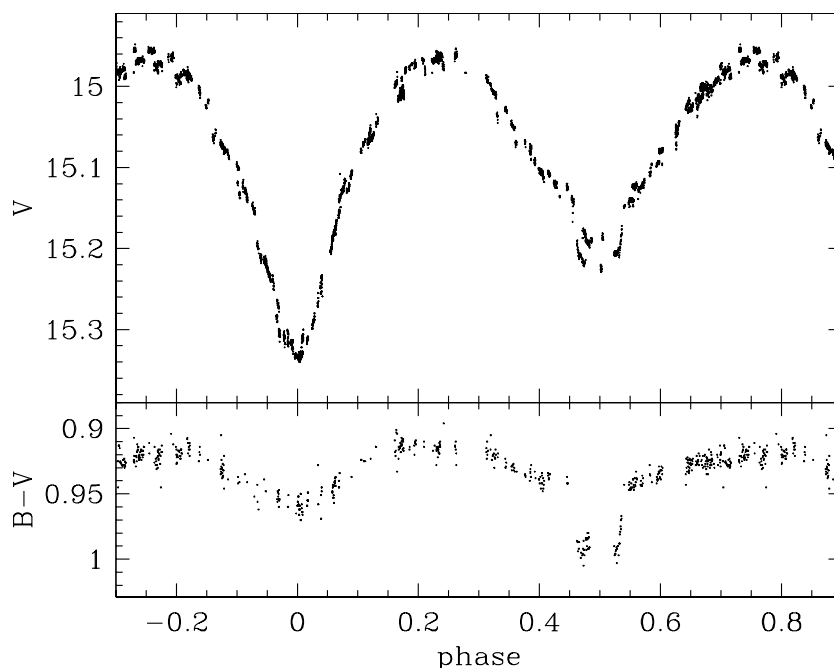
Fig. 8. Light curves of V49.

Another variable deserving a detailed study is V49. This is an eclipsing PM member of the cluster located 0.5 mag above the red giant branch at $V = 15.0$. The orbital period of 32 days, a β Lyr type light curve and the location on the CMD indicate that V49 is composed of two red giants forming a close binary. Fig. 6 shows phased $V$ and $B-V$ light curves. The secondary eclipse is total, with the ingress starting at a phase of about 0.46. The duration of totality is $\approx 0.06P$. In the secondary minimum the system becomes markedly redder, indicating that the smaller and hotter component is eclipsed. The depth of the secondary eclipse varies by $\approx 0.04$ mag; presumably due to a spot activity on at least one of the components. These variations and lack of spectroscopically determined mass ratio prevent an accurate analysis of V49, and for the moment only an approximate photometric solution is possible. We made simultaneous fits to $V$ and $B$ light curves from the 2001–2009 observing seasons using the PHOEBE package (Prša and Zwitter 2005) for a number different values of orbital inclination $i$ and mass ratio $q$. The best fit was obtained for a semidetached configuration with the primary component (*i.e.*, the one eclipsed at phase 0.0) filling its Roche lobe. We derived $q = m_s/m_p = 2.0$, $i = 78°\!.3$, the ratio of the radii $r_s/r_p = 0.21$ and the ratio of luminosities in $V$-band $L_s/L_p = 23$. Such a configuration is quite unusual, implying that the light curves are strongly dominated by the ellipsoidal variability of the less massive but larger and more luminous component. If true, the high luminosity ratio would unfortunately preclude a spectroscopic determination of the mass ratio for this interesting system.

The binary V66 with $P \approx 2.0$ d is a PM member of the cluster. However, its location 1.4 mag above the main sequence is not consistent with the presumed membership. The analysis of template images shows no evidence for any unresolved companion which could increase the observed brightness of the binary. On archival ACS/HST images only a faint ($V = 23.6$ mag) companion is seen at an angular distance of $1.\!''3$. There is still a possibility that V66 is a member of a triple hierarchical system. Such a configuration is in fact common among main sequence eclipsing binaries with a period of a few days (Tokovinin *et al.* 2006). Shallow eclipses of similar depth observed in the light curve of V66 are consistent with this possibility, although they may be equally well explained by grazing eclipses. Spectroscopic observations could clarify this issue.

Contact binaries belonging to the cluster are present only among the blue stragglers. These are the variables V39 and V59. The absence of such objects on the main sequence is remarkable. The analyzed sample included 16 200 main sequence stars with $18.5 < V < 22.0$ mag. Due to short periods and characteristic sine-like light curves, contact binaries are very easy to detect even with noisy photometry. A search for such binaries in NGC 6362 based on our data should be complete down to $V \approx 22$ mag. The paucity of contact binaries among main sequence stars was also observed in our earlier studies of globular clusters M55, M4 and NGC 6752 (Kaluzny *et al.* 2010, 2013, Kaluzny and Thompson 2009). Our findings indicate that, at least in globular clusters, the principal factor enabling contact systems to form from close but detached binaries is nuclear evolution: a contact configuration is achieved once the more massive component starts to expand quickly at the turnoff. Apparently, nuclear evolution is more important in this respect than the frequently invoked magnetic breaking; see *e.g.*, Stępień and Gazeas (2012) and references therein.

### 3.2. *Spotted Red Giants*

Besides V49, there are two other variable stars belonging to the cluster and located on or close to the red giant branch. The light curve of V68 shows a sinusoidal modulation with a period of $\approx 18$ d. This modulation is coherent over the whole duration of our observations. However the average magnitude and amplitude of the variability shows seasonal changes. If the observed variations are due to binarity then the orbital period would be two times longer than listed in Table 1. The light curve of V61 shows an incoherent, roughly sinusoidal modulation with a period of $\approx 45$ d. In Fig. 6 both V68 and V61 light curves correspond to the 2001 season.

### 3.3. *Blue Stragglers*

The CMD based on the du Pont data contains 84 candidate blue stragglers (BS) with $16.0 < V < 18.7$ mag and $0.05 < B-V < 0.49$ mag. Of these 70 are proper motion members of NGC 6362, five are field stars and for nine objects a proper motion is not available. The BS lacking a measured proper motion are located in the

very central part of the cluster and are likely members. Eight BSs are variable stars: two are contact binaries and six are SX Phe pulsators. The most interesting among the latter is V38, distinguished by pulsations with a large amplitude (0.63 mag). The fundamental radial mode is dominant with $P_1 = 0.06661582$ d, but the slightly "diffuse" light curve indicates that, like many other SX Phe stars, V38 is a multiperiodic pulsator. Indeed, we found a significant power at $P_2 = 0.05457972$ d and $P_3 = 0.04948753$ d. No variable stars were detected among candidate BSs from the outer part of the cluster found on images from the Swope telescope. An interesting interloper in the blue stragglers' region is the contact binary V56. Using the calibration of Rucinski (2000) we estimated its absolute luminosity at $M_V = 1.87$. At the observed magnitude of $V = 17.50$ mag an apparent distance modulus is $(m - M)_V = 15.63$ mag, while for the cluster we have $(m - M)_V = 14.68$ mag (Harris 1996, 2010 edition). For $A_V = 0.21$ mag the variable is located at a distance of 12.1 kpc, *i.e.*, 4.3 kpc behind the cluster. Given the Galactic latitude of $-17°6$, V56 resides about 3.7 kpc above the Galactic plane and is thus an example of a binary blue straggler from the Galactic halo.

## 4.  Summary

We conducted an extensive photometric survey of the globular cluster NGC 6362 in a search for variable stars. Twenty five new variable stars were discovered, and multi-seasonal light curves were compiled for another 44 variable stars that had been known before. For all variable stars accurate periods were obtained. One new eclipsing binary and two new pulsating stars were found in the blue-straggler region. Three of the new detached eclipsing binaries reside in the turnoff region, and another two redward of the lower main sequence. Two objects are interesting targets for follow-up observations: V65 at the turnoff and V49 on the red giant branch. V65 is a well detached eclipsing binary whose study would tighten constraints on the age and distance of the cluster provided by V40 and V41 (Kaluzny *et al.*, in preparation). V49 is the first known example of a close red-giant binary belonging to a globular cluster. As such, it is a potential source of very valuable information concerning the advanced evolutionary stages of low-metallicity stars.

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