# Photometric study of the variable star population in the globular cluster NGC 6397

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**ABSTRACT**

We present the results of a photometric survey for variable stars in the central region of the nearby globular cluster NGC 6397. Time series photometry was obtained for 30 variable objects. The sample includes 12 new objects, of which 6 show periodic light curves and 2 are eclipsing binaries of unknown period. Six variables possess certain and three possess likely X-ray counterparts detected with the *Chandra* observatory. Among them four are cataclysmic variables and one is a foreground eclipsing binary. The cataclysmic variable CV2 exhibited a likely dwarf nova type outburst in May 2003. The cataclysmic variable CV3 was observed at $18.5 < V < 20.0$ during 5 observing runs, but went into a low state in May 2003 when it reached $V > 22$. We have found that the light curve of the optical companion to the millisecond pulsar PSR J1740-5340 exhibits noticeable changes of its amplitude on a time scale of a few months. A shallow eclipse with $\Delta V = 0.03$ mag was detected in one of the cluster turnoff stars suggesting the presence of a large planet or brown dwarf in orbit.

**Key words:** novae, cataclysmic variables – stars:variables:other – globular clusters: individual: (NGC 6397)

## 1 INTRODUCTION

The central region of the post-core-collapse cluster NGC 6397 is known to contain several objects likely to have been created as a result of stellar interactions in its core region. Identification of three candidate cataclysmic variables (CVs) based on *HST* data (Cool et al. 1995; Grindlay et al. 1995) was followed by detection of 25 X-ray sources with the *Chandra* observatory (Grindlay et al. 2001). The *Chandra* sources include 8 candidate or confirmed CVs, a quiescent low mass X-ray binary and a millisecond pulsar PSR J1740 − 5340. The sample of variable stars known in the cluster field contains several pulsating SX Phe stars and contact binaries (Kaluzny 1997; Kaluzny & Thompson 2003, hereafter KT03).

In this paper, we report the results of a new photometric survey aimed mainly at the identification of detached eclipsing binaries in the central part of NGC 6397. Such objects can potentially serve as distance and age indicators for the cluster itself (Paczyński 1997). The reported survey is a part of the long-term CASE project, which has been conducted for several years at Las Campanas Observatory (Kaluzny et al. 2005). Secondary goals of the reported observations included detection of optical variability and a search for possible outbursts of CVs candidates and examination of the stability of the light curve of an optical counterpart to the millisecond pulsar (Ferraro et al. 2001).

## 2 OBSERVATIONS

All images were taken at Las Campanas Observatory with the 2.5-m duPont telescope. A field of $8.65 \times 4.33$ arcmin$^2$ was observed with the TEK No. 5 CCD camera at a scale of 0.259 arcsec/pixel. The cluster core was positioned 32 arcsec West of the field center. Observations were made on 14 nights during 4 observing runs conducted from May 2003 to June 2004. Images were taken in two bands with exposure times 10-20 s for the $V$ and 20-40 s for the $B$ filters. During the 2003 season observations were limited to the $V$ band only. In total, 1951 frames in $V$ and 288 frames in $B$ were collected and the field was monitored for 55 hours.

The raw data were pre-processed with the IRAF-CCDPROC package.[1] Groups of 3-5 consecutive frames were co-added, and the total number of stacked images used in the present study was 375 and 85, for $V$ and $B$ bands respectively. The resultant time resolution of our photometry based on combined images is about 5 minutes. The median value of seeing was 1.01 and 1.02 arcsec for the $V$ and $B$ band, respectively.

## 3 PHOTOMETRY AND IDENTIFICATION OF VARIABLES

To search for variable objects we used the ISIS-2.1 image subtraction package (Alard & Lupton 1998; Alard 2000). Our procedure followed closely that described in some detail by Mochejska et al. (2002). Instrumental magnitude zero points for the ISIS differential light curves were measured from the template images, using the DAOPHOT/ALLSTAR package (Stetson 1987), and aperture corrections were measured with the DAOGROW program (Stetson 1990). Instrumental magnitudes were transformed to the standard $BV$ system using a large assembly of local standards established during our earlier study of the same cluster (Kaluzny, Ruciński & Thompson 2003). The monitored field includes 6 stars from the Stetson (2000) photometric catalog; standard $V$ magnitudes are available for all of them. We find mean difference $\Delta V = 0.036 \pm 0.006$, in the sense that our magnitudes are brighter. $B - V$ colors are available for only two Stetson stars located in our field. We obtained $\Delta(B - V) = -0.031$ and $\Delta(B - V) = -0.032$ for Stetson objects #86 and #88, respectively (our colors are redder). Consequently we have applied corrections of $\Delta V = 0.036$ and $\Delta(B - V) = -0.031$ to our photometry. All photometric quantities listed below include these corrections.

Two methods were used to detect variable objects. The first method relies on examination of the light curves for all stellar objects detectable with the profile photometry on the reference image for the $V$ band. The PHOT procedure in the ISIS package was used to extract differential light curves at the position corresponding to each stars detected with DAOPHOT/ALLSTAR. The light curves were then transformed to magnitudes and checked for variability using the TATRY program written by ASC. This program is suitable for detection of various types of variable stars and in particular uses the AoV algorithm (Schwarzenberg-Czerny 1996) to search for the presence of any periodic signal in the analyzed light curves. The second method is based on examination of residual images produced by the ISIS package. In particular it allows searching for unresolved variables which were not detected with the profile photometry.

A total of 30 variables were identified. Their equatorial coordinates are listed in Table 1. The astrometric frame solution was derived using the coordinates of 547 stars extracted from the GSC-2 catalog with the help of the Skycat-2.7.3 interface. Names listed in column (1) of Table 1 follow Clement et al. (2001) for objects V4-24. Variables V25-36
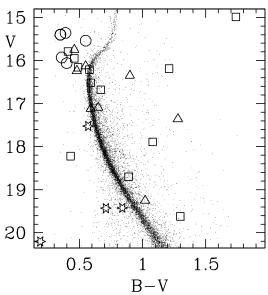
**Figure 2.** Color-magnitude diagram for NGC 6397, with positions of the variables marked. Triangles indicate eclipsing binaries, circles pulsating stars, asterisks CVs, and squares the remaining variables.

are new identifications. Column (2) gives alternate designations used in Grindlay et al. (2001). Columns (5-9) list some basic photometric properties of variables deduced from our photometry. Most of the objects can be classified as periodic variables. For objects V4-24 the listed periods were derived from photometry including observations from the 2002 season reported in KT03.

The finding charts for variables V33=CV3 and V34=CV2 can be found in Cool et al. (1995). Variable V31 can be unambiguously identified as an object located at $(X, Y) = (475, 241)$ on the HST/WFPC2-PC1 image u5dr0401r. The finding charts for the remaining new variables are shown in Fig. 1.

Positions of the variables on the cluster color-magnitude diagram are shown in Fig. 2.

### 3.1 *Chandra* sources

Based on *Chandra* deep-imaging observations, Grindlay et al. (2001) detected 25 X-ray sources within $2'$ of the cluster center. Five of the variables listed in Table 1 can be unambiguously identified as optical counterparts to the *Chandra* sources. These are cataclysmic variables CV1-3 and CV6, and an optical companion to the millisecond pulsar PSR J1740-5340 (Ferraro et al. 2001). For these objects we find mean difference of equatorial coordinates $\Delta\alpha = 0.09 \pm 0.04''$ and $\Delta\delta = 0.60 \pm 0.06''$, in the sense that *Chandra* positions are to West and South of positions derived from our frame solution. We have added the above listed offsets to coordinates of other sources reported in Grindlay et al. (2001) and looked for their possible counterparts on the list of detected variables. Variable V30 can be considered as a very likely counterpart of the *Chandra* source U5. The difference of coordinates from the two surveys amounts to 0.06 arcsec. For variables V26(U42), V31(U18) and V35(U14) the differences amount to 0.35, 0.41 and 0.38 arcsec, respectively. We note that source U18 was identified by Grindlay et al. (2001)

**Table 1.** Variable stars in the field of NGC 6397.

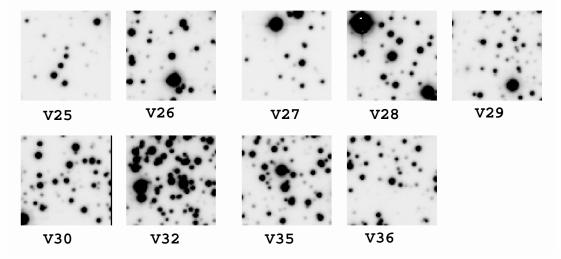| Name | ID | RA(2000) h  m  s | Dec(2000) °  ′  ″ | Period days | $V_{max}$ | $V_{min}$ | $< B - V >$ | Type/remarks |
|------|------|------|------|------|------|------|------|------|
| V4 | | 17 41 08.81 | -53 42 34.0 | 0.422740 | 16.35 | 17.08 | 0.90 | eclipsing W UMa |
| V7 | | 17 40 43.89 | -53 40 35.1 | 0.269861 | 17.09 | 17.56 | 0.65 | eclipsing W UMa |
| V8 | | 17 40 39.25 | -53 38 46.8 | 0.271243 | 16.24 | 16.62 | 0.48 | eclipsing W UMa |
| V10 | | 17 40 37.51 | -53 40 36.1 | 0.030754 | 15.93 | 16.06 | 0.36 | SX Phe |
| V11 | | 17 40 44.10 | -53 40 40.4 | 0.038262 | 15.40 | 15.45 | 0.35 | SX Phe |
| V12 | CV1, U23 | 17 40 41.57 | -53 40 19.2 | 0.471199 | 17.52 | 18.01 | 0.57 | CV |
| V13 | CV6, U10 | 17 40 48.95 | -53 39 48.5 | 0.235196 | 19.43 | 19.80 | 0.71 | CV |
| V14 | | 17 40 46.46 | -53 41 15.2 | 0.33509 | 19.25 | 19.41 | 1.02 | eclipsing |
| V15 | | 17 40 45.38 | -53 40 24.8 | 0.023824 | 15.40 | 15.46 | 0.35 | SX Phe |
| V16 | MSP, U12 | 17 40 44.59 | -53 40 41.4 | 1.35406 | 16.68 | 16.90 | 0.67 | ellipsoidal |
| V17 | | 17 40 43.78 | -53 41 16.2 | 1.061132 | 16.21 | 16.25 | 0.58 | spotted?, ellipsoidal? |
| V18 | | 17 40 43.60 | -53 40 27.6 | 0.786689 | 15.75 | 15.89 | 0.49 | eclipsing |
| V19 | | 17 40 42.81 | -53 40 23.3 | 0.253755 | 17.12 | 17.22 | 0.59 | eclipsing |
| V20 | | 17 40 41.66 | -53 40 33.1 | 0.861160 | 15.79 | 15.87 | 0.41 | γ Dor? |
| V21 | | 17 40 41.55 | -53 40 23.4 | 0.038961 | 15.32 | 15.62 | 0.39 | SX Phe |
| V22 | | 17 40 41.11 | -53 40 41.9 | 0.344 | 16.06 | 16.24 | 0.40 | RRd, P0=0.52 |
| V23 | | 17 40 39.30 | -53 40 46.5 | 0.037153 | 15.51 | 15.54 | 0.55 | SX Phe |
| V24 | | 17 40 39.07 | -53 40 22.9 | 0.457176 | 16.16 | 16.18 | 0.49 | γ Dor? |
| V25 | | 17 41 10.16 | -53 39 30.5 | 1.2306? | 17.89 | 18.06 | 1.08 | periodic? |
| V26 | U42? | 17 40 43.05 | -53 38 31.2 | ? | 16.19 | 16.28 | 1.21 | irregular |
| V27 | | 17 41 13.80 | -53 41 14.1 | 0.55614 | 18.22 | 18.27 | 0.43 | ellipsoidal? |
| V28 | | 17 41 02.70 | -53 39 47.0 | 25.997 | 14.99 | 15.27 | 1.74 | pulsating? |
| V29 | | 17 40 59.64 | -53 40 38.6 | 1.2434 | 19.62 | 19.81 | 1.30 | ellipsoidal? |
| V30 | U5 | 17 40 54.51 | -53 40 44.4 | ? | 17.36 | 17.92 | 1.28 | eclipsing |
| V31 | U18? | 17 40 42.59 | -53 40 27.1 | 1.30995 | 15.95 | 16.03 | 0.46 | ellipsoidal? |
| V32 | | 17 40 40.30 | -53 41 25.2 | ? | 16.13 | 16.16 | 0.55 | eclipsing |
| V33 | U17, CV3 | 17 40 42.62 | -53 40 19.0 | ? | 18.3 | 22.5: | 0.2: | CV |
| V34 | U19, CV2 | 17 40 42.29 | -53 40 28.6 | ? | 16.2 | 22.0: | 0.8: | CV |
| V35 | U14? | 17 40 43.31 | -53 41 55.2 | 0.298438 | 18.70 | 18.87 | 0.89 | ellipsoidal? |
| V36 | | 17 40 44.10 | -53 42 11.3 | 0.54866 | 16.52 | 16.54 | 0.59 | pulsating? |



**Figure 1.** Finder charts for some of newly identified variables. Each chart is 20″ on a side. North is up, and east to the left. Variables are located right at the center of respective images.

with BY Dra candidate or possible millisecond pulsar based on analysis of HST/WFPC2 images.

We also performed a search for possible variables by extracting, with ISIS, light curves at locations corresponding to the *Chandra* sources. This procedure gave a positive result only for U21=CV4. A clearly variable non-periodic object was detected at the predicted location of that source. However, due to crowding problems it was impossible to derive profile photometry for it and to transform its light curve from differential count units into magnitudes. We may only note that Piotto et al. (2002) obtained for CV4 $V = 20.68$ and $B = 21.49$ based on HST/WFPC2 imaging. We did not detect any variable sources at positions corresponding to candidate CVs U22=CV5, U11=CV7, U13=CV8 and U28=CV (Grindlay et al. 2001). Source U13 is located $0.8''$ from an SX Phe variable V11, while sources U22 and U28 are located very close to bright non-variable stars.

## 4    PROPERTIES OF VARIABLES

### 4.1    Cataclysmic variables

Plots of $V$ magnitude against time for cataclysmic variables CV1-3 and CV6 for the observing seasons 2002-2004 are shown in Fig. 3. Stars V12=CV1 and V13=CV6 were identified as eclipsing CVs in KT03. The light curves of both of them exhibit two distinct minima per orbital period. The shape and mean level of the optical light curve of CV6 was remarkably stable over three observing seasons. Figure 4 shows its phased light curve for the 2004 season. It is evident that the accretion rate in this system was roughly constant over the last 3 years. Also, the light curve seems to be dominated by ellipsoidal variations. The light curve of variable V12=CV1 is less stable than that of CV6. The average $V$ magnitude of the variable increased by about 0.5 mag between the 2002 and 2004 seasons. The unstable character of the light curve of CV1 is demonstrated in Fig. 5, which shows phased light curves for 4 selected nights from the 2004 season. These light curves were extracted from individual images and subsequently were smoothed using a box-car filter with $N = 3$. Effective time resolution is about 80 seconds. Besides overall changes of the shape of the eclipse, one may notice the presence of non-periodic oscillations and/or flickering with $\Delta V$ reaching about 0.15 mag. Such oscillations were not observed during the 2002 season. Our photometry of CV1 and CV6 fails to reveal any periodicities other than those related to the orbital periods. However, the limited time resolution of our data does not allow us to rule out the occurrence of short period oscillations with a time scale of the order of 10s like those observed in DQ Her type CVs or in some dwarf novae.

The light curve of variable V34=CV2 does not show any periodicity although changes of $V$ magnitude exceeding 1 magnitude were observed on several nights. The variable exhibited a likely dwarf nova type outburst in the first half of May 2003. At that time it reached $< V > \approx 16.5$, which corresponds to $M_V \approx 4.3$ for an assumed cluster membership. There is no evidence for the presence of any superhumps during the event. Unfortunately we have failed to obtain any color information during the outburst.

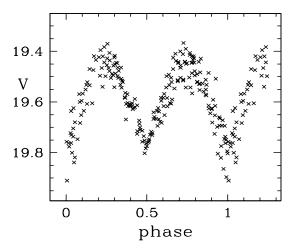The variable V33=CV3 was observed at $19.1 < V <$



**Figure 4.** Phased $V$ light curve of V13=CV6 for the observing season 2004.

19.9 in 2002 and at $18.3 < V < 19.5$ in 2004. On some nights non-periodic changes of $V$ exceeding 0.8 mag were seen. In May 2003 the star was found in a low state with $V > 22.0$. Several measurements for that run indicate $V > 22.5$ mag, although with formal errors exceeding 0.4 mag. Still, one may conclude that in May 2003 the variable was certainly below $V = 22.0$, corresponding to $M_V \geqslant 9.8$.

Grindlay et al. (1995) reported spectroscopic observations of CV1-3 obtained with the *HST* Faint Object Spectrograph. They noted in particular the presence of He II $\lambda4686$ emission lines in all three objects. That, in turn, lead to the conclusion that CV1-3 are likely magnetic CVs. Our data are insufficient to rule out the possibility that these systems indeed belong to the DQ Her type magnetic systems. However, the presented light curves do not support the hypothesis that any of the observed systems belongs to polars or intermediate polars.

### 4.2    Eclipsing binaries

The main objective of our observing program was the detection of detached eclipsing binaries belonging to the clusters. We hardly succeeded in that respect despite quite extensive time coverage (87 hours for the inner $8.65 \times 2.6$ armin$^2$ field and 55 hours for the larger $8.65 \times 4.3$ armin$^2$ field). Two new eclipsing systems were identified. A single eclipse event with $\Delta V = 0.5$ mag was observed for the variable V31. This object, possessing an X-ray counterpart, is most likely a foreground binary of late spectral type. With $V_{max} = 17.4$ and $B - V = 1.28$ it is located far to the red of the main sequence on the cluster color-magnitude diagram.

A very likely eclipsing event with $\Delta V \approx 0.03$ mag was detected for the variable V32. As one can see in Fig. 6 a flat-bottomed part of eclipse and egress were observed on the night of 11 April 2004. We checked carefully that the observed event was not caused by any sort of instrumental effects. There is also no evidence in our data that the photometry of variable is affected by any unresolved blends reducing the observed depth of a possible eclipse. Unfortunately, the variable is located outside the fields covered by *HST* images currently available publicly. Hence, we cannot exclude the possibility that, in fact, the shallowness of the observed
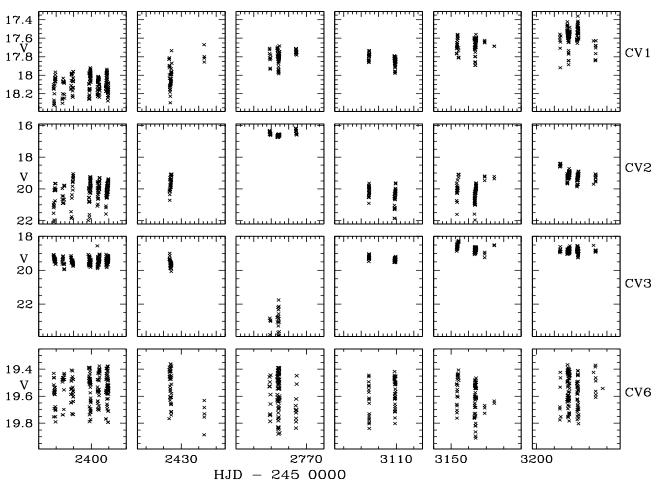
**Figure 3.** Time domain $V$ light curves of observed CVs for the period 2002-2004. Each box covers the time interval of 10 days.

eclipse like event is due to the presence of more than one star inside the fitted profile of V32. The variable is located right at the top of the cluster turnoff on the color-magnitude diagram (see Fig. 2). The light curve of V32, including 32 hours of photometry from the 2002 season, can be phased with a wide range of periods but 10 shortest of them are within a range 1.011038-1.060271 d. Other possible short periods are grouped near 2.05 and 4.15 d. It is tempting to speculate that the shallow transit like event observed in V32 is caused by a large planet or brown dwarf orbiting the turnoff star from NGC 6397. Such a possibility can be tested by spectroscopic observations as well as by further photometry aimed at determination of the orbital period and detailed analysis of shape of the eclipse. In particular, determination of the orbital period at $P \approx 1$ d would rule out a planetary transit hypothesis as it implies too wide eclipses lasting about 0.1P. Spectroscopic observations could on the other hand eliminate the possibility that V32 is a hierarchical triple system including an eclipsing binary (eg. Torres et al. 2004).

### 4.3   The optical companion to PSR J1740-5340

The variable V16 is an optical companion to the millisecond pulsar PSR J1740-5340 (D'Amico et al. 2001; Ferraro et al. 2001). Its variability is explained by the ellipsoidal effect.

The star has been recently a subject of detailed photometric and spectroscopic studies (Kaluzny, Rucinski & Thompson 2003; Ferraro et al. 2003; Orosz & van Kerkwijk 2003; Sabbi et al. 2003). In particular, modeling of the light curve served as a basis for constraining the orbital inclination of the system. It has been noted in Kaluzny et al. (2003) that the optical light curve of V16 exhibits some seasonal changes of its shape and amplitude. That claim is further supported by our new data. The phased $V$ light and color curves of V16 including the data from 2002-2004 seasons are shown in Fig. 7. Changes of the light curve level reaching 0.03 mag at a given phase are clearly visible. In particular we observed the occurrence of changes with $\Delta V \approx 0.03$ mag within the 2004 observing season spanning about 100 days. The color curve shows small orbital variations and the color becomes redder at the upper and lower conjunctions (at phase 0.5 the observer sees the side of the optical companion facing the pulsar). As was already noted in Ferraro et al. (2003), the lack of pronounced orbital variations of the color index is puzzling, considering detection of high excitation He I absorption lines in the spectrum of V16.

**Table 2.** List of frequencies identified in SX Phe stars.

| Star | $A_0$ | $f_0$ | $f_1$ | $f_2$ | $f_3$ | $f_4$ | $f_5$ |
|------|-------|-------|-------|-------|-------|-------|-------|
| V10 | 0.0214(18) | 32.51591(8) | 33.30011(9) | 31.84787(12) | | | |
| V11 | 0.0202(3) | 26.13539(2) | *27.01135(8)*† | *30.61296(14)*† | | | |
| VV15 | 0.0135(5) | 46.61237(3) | 42.05000(4) | *39.79092(6)* | *40.35747(7)* | 27.80867(6) | *42.11866(10)* |
| V21 | 0.1351(17) | 25.66644(1) | 29.31764(10) | | | | |
| V23 | 0.0084(5) | 26.91564(5) | 26.26072(9) | 49.23396(12) | | | |

Remarks:

*italics* indicate modes which yield clear spectral pattern, yet frequency is subject to alias ambiguity;
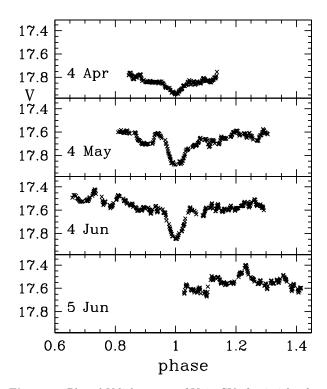
† cycle/year alias ambiguity;



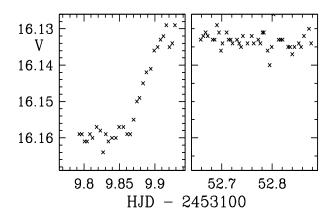**Figure 5.** Phased *V* light curves of V12=CV1 for 4 nights from the observing season 2004.



**Figure 6.** *V* band light curves of variable V32 obtained on nights of 2004 April 11 and May 27.
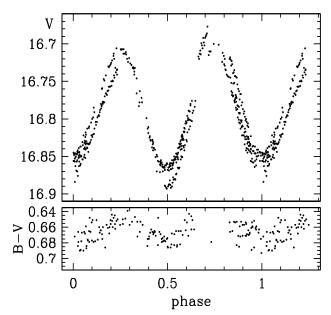


**Figure 7.** Phased light and color curves of variable V16.

### 4.4   SX Phe stars

Detailed discussion of properties of SX Phe variables from NGC 6397 is beyond the scope of this paper. We decided, however, to provide a list of periods detectable in our time series photometry. As it turns out, all the objects show multi-periodic pulsations which is a very common property of low amplitude SX Phe stars (eg. Rodríguez & Breger 2001).

Analysis of observations of SX Phe stars was repeated in two different ways: either by iterations involving alternative period search and prewhitening of the original data with all periods identified so far, or by successive prewhitening of one period at a time and period search in the residuals. For period search we employed the multi-harmonic analysis of variance periodogram (mhAoV, Schwarzenberg-Czerny, 1996). The periodogram is based on fitting data with an orthogonal Fourier series. In the present case the series involved the fundamental frequency and its first harmonic. This aided in identification of the stronger, non-sinusoidal modes without much affecting detection of the faint, sinusoidal modes. The advantage in employing Fourier series, as opposed to a plain sinusoid, is two-fold: harmonics tend to increase the detected power and they no longer contribute to the residual noise. Fourier series or phase binning in any pe-
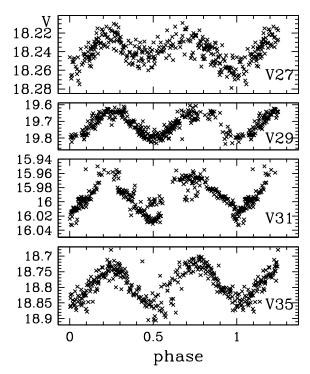
**Figure 8.** Phased light curves of new candidate ellipsoidal variables.



**Figure 9.** Phased light curves of variables V28 and V36.

riodogram produce sub-harmonics as their side effect. These pose no practical difficulty as they stand-out by their tight spacing of aliases.

Results of the analysis are presented in Table 2 which for each star lists an amplitude for the strongest mode of pulsation along with all detected frequencies.

### 4.5 Other variables

The old variable V22 can be now classified as a double mode RRd variable located in the cluster background. The available data allow preliminary determination of the fundamental period and its first overtone at $P0 = 0.52$ d and $P1 = 0.344$ d, respectively.

Four objects from the sample of newly detected variables were classified preliminarily as ellipsoidal variables. Their light curves show periodic sinusoidal modulations. This is illustrated in Fig. 8, which shows phased light curves for the relevant stars. In the case of V31 the observed scatter reflects mainly the change of average magnitude between 2003 and 2004 seasons. Spectroscopic data are needed to verify the proposed classification and to establish the membership status of these stars.

Figure 9 shows light curves of V28 and V36 phased with the periods listed in Table 2. These two stars are preliminarily classified as pulsating variables as stability of their light curves seems to exclude belonging to spotted variables.

The light curve of V25 for the 2004 observing season showed periodic modulation with $P = 1.2306$ d. However, this periodicity is absent in the data from the 2003 season.
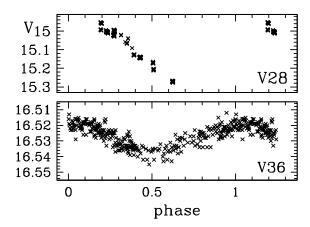
## 5  SUMMARY

Our observing program was focused on the detection of detached eclipsing binaries in NGC 6397. Although two such objects were identified, none of them can serve as an age or distance indicator for the cluster. The binary V30 is most likely a foreground field star. The second object, V32, has a good chance of being a cluster member but showed a single, very shallow eclipse. It could be composed of a cluster upper main sequence star orbited by a dim companion being a large planet or brown dwarf. Another possibility is that we have observed a grazing eclipse in an otherwise normal binary. However, the shape of the light curve inside the observed eclipse does not favor the latter alternative. At $V = 16.1$ the star is sufficiently bright for spectroscopic follow-up observations.

Our sample includes several candidates for ellipsoidal variables. Some of them, primarily these located among blue stragglers or close to the cluster main sequence, are also interesting candidates for spectroscopic follow-up. Because of their location in post-core-collapse cluster some of them may be detached binaries with degenerate components.

Based on observations from 3 observing seasons we have refined the determination of orbital periods for two cataclysmic variables, CV1 and CV6. A very likely dwarf nova type outburst was detected for the variable CV4. None of the four observed CVs showed any evidence of photometric variability pointing to its association with magnetic systems. Finally, our extensive and homogeneous photometry shows unambiguously that the light curve of the optical companion to the millisecond pulsar PSR J1740-5340 exhibits seasonal changes of its amplitude.

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