SX Phoenicis Stars in the Globular Cluster M 92

G. Kopacki

Astronomical Institute, University of Wrocław, Kopernika 11, 51-622 Wrocław, Poland
e-mail: kopacki@astro.uni.wroc.pl

Received February 22, 2007

ABSTRACT

We present results of a search for SX Phe stars in the globular cluster M 92. In photometric reductions, we used the image subtraction method supplemented with a procedure of searching for short-period variables, based on the examination of each pixel in the CCD frame. In addition to two SX Phe stars already known in the cluster, we have found five new variables of this type. One SX Phe variable, v34, shows double-mode pulsation with a period ratio equal to 0.741 or 0.790. The second value would indicate oscillations in radial fundamental and first overtone modes. Combining our ground based data and the WFPC HST observations, we determine the average $V$ magnitudes and $(V−I_C)$ colors for three SX Phe stars. Moreover, from an estimate of the scatter in the HST data of all observed blue stragglers we suspect three stars to be variable.

Key words: Stars: Population II – globular clusters: individual: M 92

1. Introduction

This is the second paper in a series devoted to a search for SX Phe stars in globular clusters, using small telescope and the image subtraction method of photometric reduction. The method, based on the derivation of the light curve for every pixel in the CCD frames, was presented in the first paper (Kopacki 2005), where the results for the cluster M 13 were also given.

SX Phe stars are short-period ($P < 0.15$ d) pulsating stars occupying the lower part of the Cepheid instability strip in the H–R diagram. They are Population II counterparts of δ Sct stars and are mainly found in globular clusters. A catalog of 122 SX Phe stars in 18 globular clusters was published by Rodríguez and López-González (2000). Several studies appeared recently increasing significantly the number of SX Phe stars known in globular clusters (see Olech et al. 2005).

M 92 (NGC 6341) is a bright northern hemisphere globular cluster of very low metallicity, [Fe/H] = −2.24. The population of variable stars in this cluster is quite diverse; it includes RR Lyr stars, one Population II Cepheid, and SX Phe stars (Kopacki 2001). Altogether, 20 confirmed variable stars are known in M 92, all belonging to the class of pulsating stars.
In this paper we report the results of the reanalysis of our data on M 92, combined with the HST observations of the cluster.

2. Data Reductions and Results of the Variability Search

We used two data sets. The first one included the same ground based CCD observations that were analyzed by Kopacki (2001). These observations were obtained in two seasons: on 9 nights in the summer of 1998 and on 17 nights in the summer of 2000. The second data set consisted of archival HST WFPC2 observations made with the filters F555W (hereafter $V$) and F814W ($I_C$).

In our previous search for variable stars in M 92 (Kopacki 2001) we looked for local brightenings in the “variability map”, defined as an average of the absolute values of all difference frames produced by the image subtraction method. Such a map shows the accumulated contribution of all flux variations with respect to the reference frame. Using the variability map of M 92, we found two SX Phe stars, v33 and v34. These two stars can be easily identified in Fig. 1.

As shown by Kopacki (2005), detection of variable stars using the variability map may be limited to relatively high amplitudes of flux changes. The method based on Fourier analysis of the light curves from all pixels in CCD frames gives much more complete results. In order to search for other possible SX Phe stars in M 92 with this method, the ground based data of Kopacki (2001) were reduced once again using the Optimal Image Subtraction Method (OISM) of Alard and Lupton (1998). The complete reduction procedure was described by Kopacki (2005). We refer the reader to that paper for details.

Pixel photometry was obtained from difference frames, that is, the light curves were determined by profile fitting photometry with centroid positioned on each pixel. Next, Fourier spectra of all these light curves were computed in the frequency range from $0 \text{ d}^{-1}$ to $30 \text{ d}^{-1}$. In this way, for each of the $560 \times 380$ pixels in the reference frame, the signal-to-noise (S/N) ratio of the highest peak in the spectrum and its frequency were determined. For every pixel close enough to the true variable star, the S/N will be higher than some assumed detection limit.

In a plot of the S/N of the highest peak in the power spectrum as a function of the corresponding frequency for all pixels, groups of points that stand out at some specified frequency and/or its aliases indicate different variable stars (moreover, all pixels in a given group should be very close each to other, forming a compact spot in the frame). A figure of this kind clearly distinguishes RR Lyr and SX Phe stars (for example see Fig. 2 in Kopacki 2005). A part of this relationship for M 92, covering only frequencies typical for SX Phe stars, is shown in Fig. 2. There are seven groups of points with high S/N, corresponding to seven variable stars: v33 and v34 discovered by Kopacki (2001), and five new variable stars which we name v35 through v39, extending the numbering scheme of the Catalog of Variable Stars in Globular Clusters (CVSGC, Clement et al. 2001). Positions of the new SX Phe
Fig. 1. Central part of the variability map, covering $3^\prime 9 \times 3^\prime 5$ field in the core of M 92. North is up, East to the left. Pulsating stars are indicated with the following symbols: the BL Her star with a diamond, RR Lyr stars with squares, and SX Phe stars with triangles. Open circles indicate positions of the blue stragglers suspected of variability. In addition, SX Phe stars are labeled with their names given in Table 2; v33 and v34 were found by Kopacki (2001), the other SX Phe stars were discovered in this paper. The other star-like objects are artefacts of the reduction method.

Fig. 2. Amplitude to noise ratio (S/N) of the highest peak in the power spectrum plotted against its frequency. Each point corresponds to one pixel in the reference frame. Frequencies cover only the range where the variability of the detected SX Phe stars is pronounced. The groups of pixels corresponding to the same variable star are shown with different symbols. The adopted designations of the variable stars are given above the arrow-heads.
variables are indicated in the variability map in Fig. 1. No clear brightenings at the positions of these stars can be seen in Fig. 1.

Fig. 3. Central part of the observed by us field in M 92 with the outline of the HST WFPC2 camera coverage. The small rectangle in the middle corresponds to the PC1 camera, the other three larger rectangles, to WF4, WF3, and WF2 (clockwise starting from PC1). Positions of two previously known SX Phe stars are shown with squares. Five new variable stars of this type are indicated with diamonds. The three stars suspected of variability are shown with circles.

The OISM reductions give light curves expressed in the flux units only. In order to convert them to magnitudes, we need an independent estimate of the magnitude of a given star, at least for a single epoch. All SX Phe stars, except v37, are located in the crowded central region of the cluster where the DAOPHOT aperture photometry is unreliable. For v37 we also could not estimate reliably its brightness from our ground based data because of its proximity to a bright star (see Fig. 3).

Among the archival WFPC HST data we found one set consisting of six $V$ and six $I_{{C}}$ frames covering the area where variables v33, v34, and v36 are located. An outline of the WFPC field is shown in Fig. 3. The observations were taken within the HST proposal GO 5969. We downloaded the data from the Multimission
Archive at Space Telescope (http://archive.stsci.edu). In order to extract standard \( V_{IC} \) magnitudes for these three stars, we processed the WFPC data with the HST-PHOT package of Dolphin (2000a, 2000b). We followed the standard procedure of reductions as described in the manual to this package. Conversion of the OISM light curves into \( V \) magnitudes was performed in the same way as in Kopacki et al. (2003).

![Fig. 4. Combined scatter in the light curves of the blue stragglers observed in the WFPC frames of M 92 as a function of mean \( V \) magnitude (left panel) and \( (V - I_C) \) color (right panel). Diamonds indicate variable stars and triangles show stars suspected of variability because of the scatter in their light curves greater than a threshold of 0.04 mag, indicated with the dashed line.]

**Table 1**

<table>
<thead>
<tr>
<th>Var</th>
<th>( \alpha_{2000} )</th>
<th>( \delta_{2000} )</th>
<th>( V )</th>
<th>( V - I_C )</th>
<th>( \sigma )</th>
<th>( \sigma/e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>s1</td>
<td>17(^{h})17(^{m})08(^{s}).39</td>
<td>43°08′21″6</td>
<td>16.82</td>
<td>0.11</td>
<td>0.086</td>
<td>17.9</td>
</tr>
<tr>
<td>s2</td>
<td>17(^{h})17(^{m})07(^{s}).18</td>
<td>43°08′10″2</td>
<td>17.38</td>
<td>0.17</td>
<td>0.083</td>
<td>16.3</td>
</tr>
<tr>
<td>s3</td>
<td>17(^{h})17(^{m})05(^{s}).99</td>
<td>43°08′17″3</td>
<td>17.87</td>
<td>0.25</td>
<td>0.056</td>
<td>8.9</td>
</tr>
</tbody>
</table>

Although the number of the WFPC frames is rather small, we used them to look for signs of variability in all blue stragglers included in the frames. For this purpose, we checked the scatter in their light curves. From the color–magnitude diagrams of the four WFPC fields indicated in Fig. 3 we selected all stars falling in the blue straggler region. We found 21 such stars in the PC1 field, five in the WF2 field, five in the WF4 field, and surprisingly none in the WF3 field. For each star we determined the combined scatter, \( \sigma \), defined as \( \sigma^2 = (\sigma_V^2 + \sigma_I^2) \), where \( \sigma_V \) and \( \sigma_I \) are standard deviations of the \( V \) and \( I_C \) data, respectively. This parameter is shown in Fig. 4 as a function of the mean \( V \) magnitude and the mean \( (V - I_C) \) color. As can be seen from Fig. 4, six stars show scatter greater than an assumed threshold of 0.04 mag. Three of these stars (v33, v34, and v36) are in fact variable, and the
remaining three we consider to be suspected of variability. We name these suspects s1, s2, and s3, and give their astrometric and photometric parameters in Table 1. For each object we provide equatorial coordinates, \((\alpha, \delta)\), mean brightness in \(V\), mean color index \((V - I_C)\), combined scatter \(\sigma\), and the ratio \(\sigma/e\) of the scatter to the single point magnitude error.

![Diagram showing light curves of suspected blue stragglers](image_url)

Fig. 5. WFPC \(V\)-filter (circles) and \(I_C\)-filter (squares) light curves of the three blue stragglers suspected of variability. For comparison, the bottom panel shows data for a constant star. DI is a magnitude shift applied to the \(I_C\) data. The ordinate scale in all panels is the same.

The light curves of the blue stragglers suspected of variability are shown in Fig. 5. We can see both the differences in the mean level between two groups of data (for each filter) and phases of steady increase or decrease in brightness within a single group. These stars are also indicated in Fig. 1 and Fig. 3. All of them are located in the central PC1 field. These stars are most probably of the SX Phe type, but other types of variability (e.g., eclipsing stars) cannot be ruled out.

3. Fourier Analysis of the Photometry of SX Phe Stars

As noted above, we identified seven SX Phe stars in the field of M 92 we observed, of which five are new. In order to determine periods of variability of these stars, we analyzed their light curves with the Fourier periodogram method. Most of the detected SX Phe stars exhibit simple mono-periodic behavior. An example of the amplitude spectrum of such variable, v33, of original data and after prewhitening with the only frequency, is shown in Fig. 6. In some cases, harmonic frequencies up to second order showed up in the power spectra. They were removed in the process of prewhitening of the original data. Our data suffer from two aliasing problems, one caused by the one-day sampling, and the other, connected to the two-year gap between the two observing seasons.
One SX Phe star, v34, turned out to exhibit double-mode pulsations. It was already discovered by Kopacki (2001), but was not inspected for multiperiodicity. Because of the strong period ambiguity in the Fourier spectrum, we used for this stars an Analysis of Variance (AOV) periodogram of Schwarzenberg-Czerny (1996). The main advantages of the AOV method are improvement in detection sensitivity and the damping of alias periods. The AOV periodograms for v34 showing the process of the light curve prewhitening are presented in Fig. 7.

Fig. 6. Fourier amplitude spectra of v33: (a) for original $V$-filter observations, (b) after prewhitening with frequency $f = 13.316554 \, \text{d}^{-1}$ and its harmonics.

Fig. 7. AOV periodograms of v34: (a) for original $V$-filter observations, (b) after prewhitening with frequency $f_1 = 12.04619 \, \text{d}^{-1}$, (c) after removing frequencies $f_1$ and $f_2 = 16.25323 \, \text{d}^{-1}$.
The ratio of the periods for the double-mode SX Phe star v34 is equal to $P_2/P_1 = 0.741$. The theoretical period ratios for the first three radial modes taken from Santolamazza et al. (2001), together with the observed values for SX Phe variables in two well studied globular clusters, ω Cen and NGC 5466, are shown in Fig. 8. We also indicate in this figure the radial double-mode candidate SX Phe star discovered by Kopacki (2005) in M 13. As can be seen, the period-ratio of the first overtone to the fundamental radial mode for SX Phe pulsators with metallicity $[\text{Fe/H}]$ in the range between $-1.3$ and $-2.3$ falls in the range from 0.77 to 0.79. In the case of the second to first overtone period-ratio, the same metallicity range corresponds to a period ratio from 0.81 to 0.82. The observed period ratio of v34 falls outside these two ranges.

It is possible, however, that due to the strong $1 \text{ d}^{-1}$ aliasing, the primary and secondary frequencies we derived are incorrect. The strongest alias of the $f_2$ frequency, $f_2 - 1 \text{ d}^{-1}$, has almost the same height as the central peak. Taking this alias as the true component, the period ratio would be equal to 0.790. This value (shown as asterisk in Fig. 8) agrees very well with theoretical predictions for double-mode radial pulsations in low metallicity SX Phe stars. It seems quite possible that v34 is a variable pulsating simultaneously in the radial fundamental and first overtone modes. To resolve this ambiguity, however, further observations are needed.

The phase diagrams of the four SX Phe variables, v35, v37, v38, and v39, are shown in Fig. 9. For these stars only differential fluxes could be derived. In Fig. 10
we show light curves of v33, v34, and v36. Here the brightness is expressed in magnitudes. The HST observations are also plotted for these stars. The photometric parameters of SX Phe stars are listed in Table 2. For each variable we provide designation, equatorial coordinates, \((\alpha, \delta)\), period(s), \(P\), epoch(s) of light maximum, \(T_{\text{max}} = \text{HJD}_{\text{max}} - 2451700\), signal-to-noise ratio, S/N, and where possible, the intensity-weighted mean brightness in \(V\), mean color index \((V - I_C)\), and range of variability, \(\Delta V\). The \((V - I_C)\) color is only a crude estimate based on the very sparse \(I_C\)-filter WFPC data. Periods are given with accuracy resulting from the non-linear least-squares fit of truncated Fourier series to the observations. The S/N is defined as the amplitude in the Fourier spectrum for a given frequency to the average amplitude after prewhitening with all frequencies.
### Table 2
Photometric data for SX Phe stars in M 92

<table>
<thead>
<tr>
<th>Var</th>
<th>$\alpha_{2000}$</th>
<th>$\delta_{2000}$</th>
<th>$V$ [mag]</th>
<th>$V - I_C$ [mag]</th>
<th>$\Delta V$ [mag]</th>
<th>$P$ [d]</th>
<th>$T_{\text{max}}$ [d]</th>
<th>S/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>v33</td>
<td>17h 17m 03s 85</td>
<td>43° 08' 13'' 7</td>
<td>17.29</td>
<td>0.17</td>
<td>0.68</td>
<td>0.07509450(4)</td>
<td>0.0538</td>
<td>30.1</td>
</tr>
<tr>
<td>v34</td>
<td>17h 17m 09s 95</td>
<td>43° 07' 42'' 7</td>
<td>17.13</td>
<td>0.29</td>
<td>0.34</td>
<td>0.0830138(1)</td>
<td>0.0287</td>
<td>15.2</td>
</tr>
<tr>
<td>v35</td>
<td>17h 17m 09s 49</td>
<td>43° 08' 38'' 0</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.0549107(1)</td>
<td>0.0361</td>
<td>9.3</td>
</tr>
<tr>
<td>v36</td>
<td>17h 17m 06s 52</td>
<td>43° 07' 57'' 4</td>
<td>17.88</td>
<td>0.32</td>
<td>0.04</td>
<td>0.04746133(7)</td>
<td>0.0149</td>
<td>9.2</td>
</tr>
<tr>
<td>v37</td>
<td>17h 17m 06s 33</td>
<td>43° 09' 48'' 3</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.04019309(7)</td>
<td>0.0101</td>
<td>8.0</td>
</tr>
<tr>
<td>v38</td>
<td>17h 17m 04s 59</td>
<td>43° 08' 45'' 2</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.07294578(6)</td>
<td>0.0653</td>
<td>15.1</td>
</tr>
<tr>
<td>v39</td>
<td>17h 17m 04s 24</td>
<td>43° 08' 50'' 4</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.03591956(7)</td>
<td>0.0033</td>
<td>6.2</td>
</tr>
</tbody>
</table>

#### 4. Color–Magnitude Diagram

The $V$ vs. $(V - I_C)$ color–magnitude diagram (CMD) for the cluster is shown in Fig. 11. The photometric data for stars brighter than $V = 17$ mag were taken from Kopacki (2001), while the faint part of the diagram is based on the data obtained from the HST frames.

From the comparison of the fiducial lines of the red giant and horizontal branches in the ground and space based $V I_C$ CMDs we found the $V$ magnitudes to be the same, but the $(V - I_C)$ colors of the HST data to be shifted by $-0.06$ mag (for PC1 camera) and $-0.08$ mag (for WF2, WF3, and WF4 cameras) with respect to our observations. We applied these corrections to all colors and $I_C$ magnitudes derived from the HST observations.

Three different types of pulsating stars in the classical instability strip, that is, BL Her, RR Lyr, and SX Phe variables, are clearly visible in Fig. 11. We also show the SX Phe candidate stars.

As can be seen from Fig. 11, all SX Phe stars occupy the blue straggler region, being brighter and bluer than the turn-off point. This location indicates that they are likely to be cluster members. Both the confirmed and suspected SX Phe stars fall on the extension of the main sequence. Only the double-mode pulsator, v34, seems to be more evolved.

#### 5. Summary

We have presented the results of a comprehensive search for SX Phe stars in the globular cluster M 92. Using slightly modified version of the image subtraction method we were able to identify seven SX Phe variables. Five of them are new. For all these stars we derived periods and showed complete light curves. One SX Phe
Fig. 11. Combined color–magnitude diagram for M 92. The upper part ($V < 17$ mag) was taken from Kopacki (2001), the lower one ($V > 16.5$ mag) is based on the photometric data obtained from the HST WFPC2 frames. SX Phe stars ($v33$, $v34$, and $v36$) are indicated with triangles, RR Lyr variables with open squares and Population II Cepheid with diamond. Asterisks show blue stragglers ($s1$, $s2$, and $s3$) suspected of variability.

star, $v34$, shows double-mode pulsations. Its period ratio is equal to 0.741 or 0.790. The second value, if real, indicates pulsations in two radial modes, fundamental and first overtone.

Combining our data with the archival HST observations of the cluster we determined average $V$-magnitudes and $(V - I_C)$ colors of three variable stars we studied. From the consideration of the scatter in the HST data of all stars falling within the range of blue stragglers we indicated three stars suspected of variability most probably of the SX Phe type.

Acknowledgements. This work was supported by Polish MNiSW grant N203 014 31/2650. Some of the data presented in this paper were obtained from the
Multimission Archive at the Space Telescope Science Institute (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NAG5-7584 and by other grants and contracts.

REFERENCES