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Variable stars in the globular cluster M5: application of the image subtraction method

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ABSTRACT

We present *V*-band light curves of 61 variables from the core of the globular cluster M5 obtained using a newly developed image subtraction method (ISM). Four of these variables were previously unknown. Only 26 variables were found in the same field using photometry obtained with DOPHOT software. Fourier parameters of the ISM light curves have relative errors up to 11 times smaller than parameters measured from DOPHOT photometry. We conclude that the new method is very promising for searching for variable stars in the cores of the globular clusters and gives very accurate relative photometry with quality comparable to photometry obtained by the *Hubble Space Telescope*. We also show that the variable V104 is not an eclipsing star as has been suggested, but is an RRc star showing non-radial pulsations.

Key words: stars: variables: other – globular clusters: individual: M5.

1 INTRODUCTION

The globular cluster M5 (NGC 5904) contains one of the richest sets of variable stars in the Galaxy. It is located only two degrees from the celestial equator and therefore it is often a target of variable stars searches from both hemispheres. Recent studies include those by Reid (1996), Sandquist et al. (1996), Drissen & Shara (1998), Kaluzny et al. (1999a,b) and Caputo et al. (1999).

Crowding effects make it very difficult to obtain reliable photometry of variable stars located near the central regions of globular clusters. One solution is to use the *Hubble Space Telescope* (*HST*). Drissen & Shara (1998) observed a $70 \times 70\,\mathrm{arcsec}^2$ field located in the centre of M5, detecting 29 variables during a 12 h run during which they obtained 22 exposures. The obvious disadvantage of using the *HST* for studies of variable stars in the cores of clusters is the difficulty of obtaining the long observational runs which are essential for good coverage of the light curves.

An alternative method is to use image subtraction which effectively deals with the problem of crowding. Recently, Alard & Lupton (1998) presented a new method of image subtraction (ISM), which actually works best in crowded fields since in this case all pixels in the image are used for the determination of the convolution kernal. Alard (1999b) modified the code of Alard & Lupton (1998) to optimally process regions of any stellar density. Alard (1999a) applied this revised formalism to the OGLE observations of Baade's Window (Woźniak & Szymański 1998) and obtained much better light curves of the microlensing events than those measured using traditional methods such as DOPHOT software (Schechter, Mateo & Saha 1993).

We decided to check the usefulness of this method for observing the light curves of variable stars in the cores of globular clusters by analysing *V*-band CCD photometry of M5 taken in 1997 May and June using the 1-m Swope telescope at Las Campanas Observatory. The main goal of these observations was to search for main sequence eclipsing binary stars and therefore the exposure times were long. As a result, these data are not favourable for observations of RR Lyr variables since these stars are bright enough near maximum light to be saturated on some of our CCD images. Exposure times ranged from 300 to 500 arcsec with median seeing of 1.5 arcsec. In spite of this, we obtained reliable photometry of 65 RR Lyr variables using DOPHOT (Kaluzny et al., 1999b). These 65 variables were detected over the whole field of view of the 2048×2048 CCD camera. For the purpose of this test application of image subtraction we have narrowed the field of view to 601×601 pixels covering $4.4 \times 4.4\,\mathrm{arcmin}^2$ of the central part of M5. This field contains 26 variables which were detected by Kaluzny et al. (1999b). Our data

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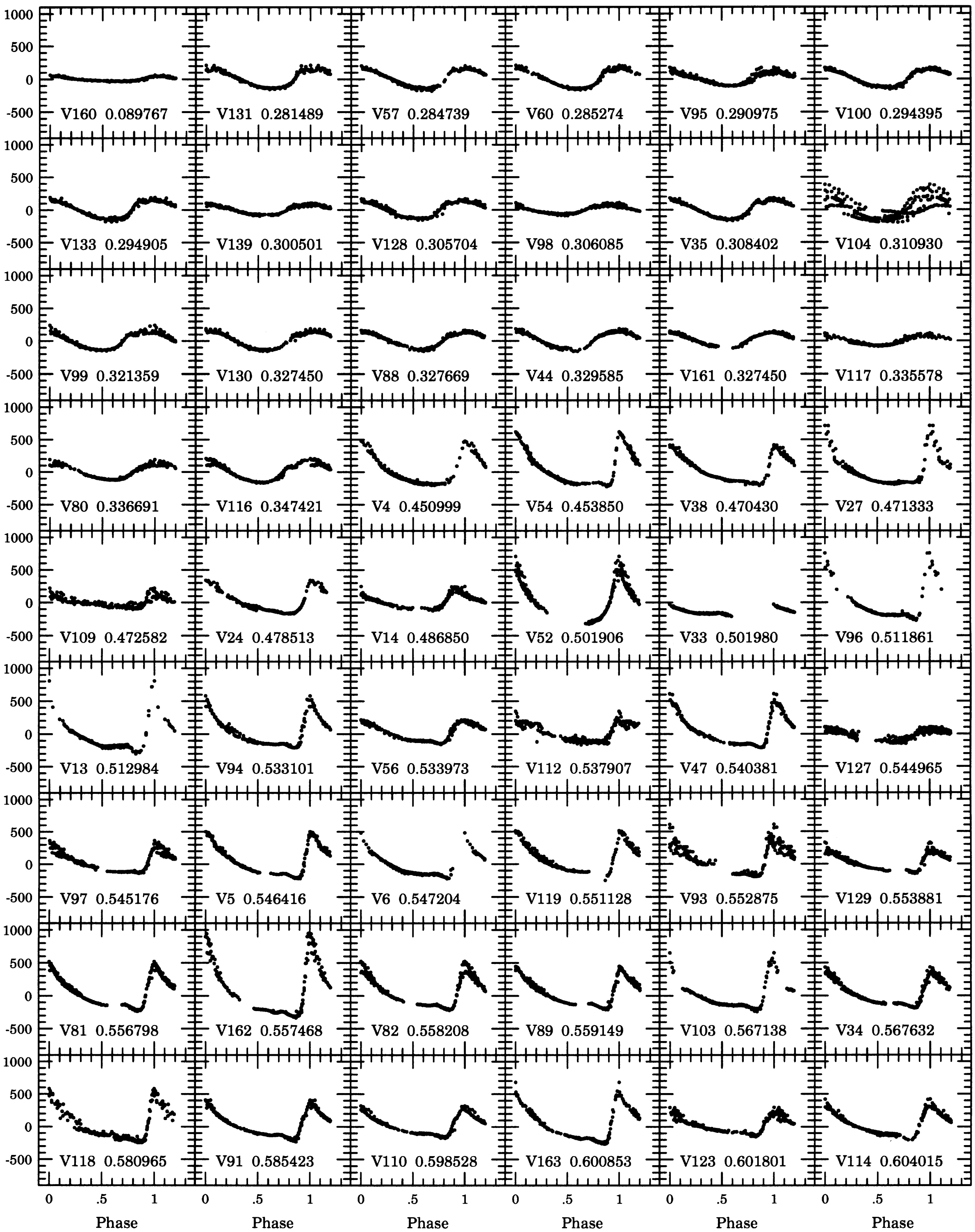

Figure 1. Light curves of the variable stars found in the core of M5. The stars are plotted according to the increasing period. The integral from 0 to P from the light curve of each star is always zero. The ordinate is plotted in units of ADU s^{-1}.

set is somewhat smaller than used by Kaluzny et al. (1999b), only observations taken in 1997 May and June analysed for a total of 161 frames. In our work we did not include over 100 frames of M5 obtained between 1997 July and August owing to the completly different parameters of the CCD camera used at that time.

2 DATA REDUCTION

Initial reductions of the CCD frames consists of bias and flat-field corrections followed by the removal of cosmic ray events. This was carried out with the IRAF package. The next important step is the registration of all frames on to a common pixel grid. This was

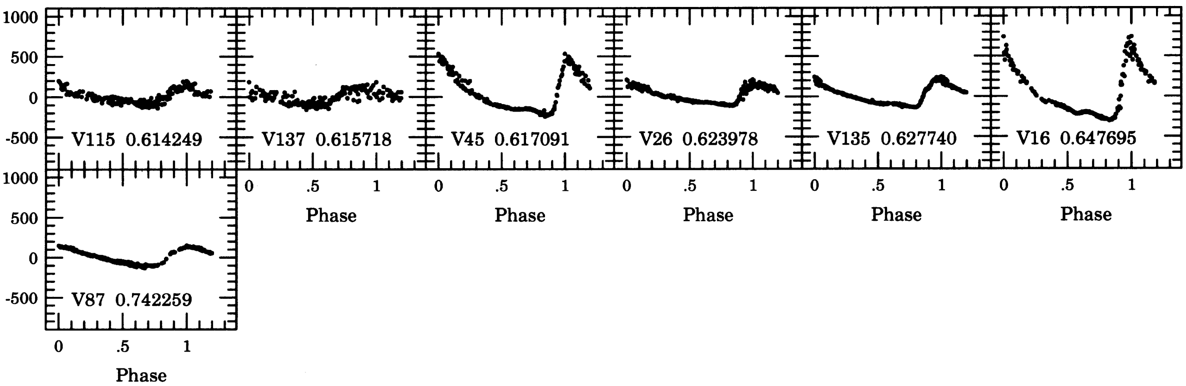

Figure 1 – *continued*

accomplished by using the centroids of approximately 640 bright unsaturated stars found in both the test image and the reference image. Strong stellar density gradients in a globular clusters can result in a fit of the coordinate transformation which is strongly dominated by distortions in the densest part of the image. An approximate equalization of the number of stars used in the fit by taking the 40 brightest stars in squares of 150×150 pixels is sufficient to avoid this problem. In the end we fitted the coordinate transformation with second order polynomials. These fits are used with a bicubic spline interpolator to resample all of the images on to the pixel grid of the reference image.

The preparation of the reference image warrants a few words of discussion. The benefits of carefully constructing this image, which will be subtracted from all of the test images, are substantial. The average of the 20 best seeing frames with low background (after resampling to the same pixel grid) is practically noiseless compared to a single exposure. This is essential if we are to approach the best possible accuracy. For many data sets the difference frames will be limited only by the photon noise of a single test frame.

Registered frames are then processed with the image subtraction code described by Alard & Lupton. The reference image is degraded to the seeing of each frame and the deviation between the two images is minimized. Areas covered by brightest stars and variables are not included in the fit. For a thorough explanation of the method we refer to the original paper of Alard & Lupton (1998). Small PSF gradients are taken into account by subdividing each frame into 3×3 subframes before fitting the convolution kernel.

Variables are detected using the 'variability image', an average of the absolute values of all difference images, which contains the accumulated contributions from all (positive and negative) variations with respect to the reference image. The PSF shape of the stellar images is preserved in the variability image, and therefore practically any software for the detection of stars can provide a list of candidate variables. Our star finding program is based on the properties of the cross-correlation image with the approximate Gaussian model of the PSF. The cross-correlation function, calculated here as the convolution with the lowered Gaussian filter, has maxima at the positions of stellar objects. Comparison of the signal with the estimated noise for each candidate constitutes the final selection criterion. We experimented with various sigma cuts and found a sharp transition between a regime where new detections are still almost entirely variables and a regime where the candidate list grows by accumulation of noise features and CCD defects. We imposed a cut-off of 4 sigma for the detection of a candidate variable.

The actual profile photometry on individual difference images is carried out using the PSF for the reference image convolved with the best-fitting PSF matching kernel for each test image. We modelled the first-order spatial variation of the PSF in the reference image using the code written for the DENIS survey (Alard, in preparation).

3 RESULTS

The overall quality of our data set was not very good, and the photon noise limit was not achieved. This is because of the combined effects of a slight non-linearity at the level of 4 per cent and residual differential refraction which just starts being noticeable in the standard *V* photometric band (see Alcock et al. 1999 for a description of the phenomenon and correction). As a result of this the final accuracy was about 3 times the photon noise. Despite these imperfections, the final light curves are very good and the power of the method to detect variables in the core of this cluster is impressive. In addition, we expect that many variables were lost because of heavy saturation of bright stars near the centre of the cluster.

In the 4.4×4.4 arcmin^2 field covering the core of M5 we detected 61 variables. The light curves of these stars are plotted in Fig. 1, and the coordinates and periods are presented in Table 1. The coordinates of the previously known variables are taken from Sawyer Hogg (1973) and Sandquist et al. (1996). The numbering scheme for variables from V1 to V103 was taken from Sawyer Hogg (1973) and from V104 to V159 from Caputo et al. (1999), who rationalized many lists of variables into a common numbering scheme. Four of our variables are new discoveries, and are labelled V160 through V163. A total of 60 of our variables are RR Lyr stars, with 19 variables belonging to Bailey type c and 41 to Bailey type ab. We found one SX Phe variable. We present finder charts for the newly discovered variables in Fig. 2.

3.1 Comparison with the results of Kaluzny et al. (1999b)

It is worthwhile to compare photometry measured from difference images presented here with values measured with the DOPHOT software. This comparison is shown in Fig. 3, where we have plotted the light curves of three typical variables (V27, V54 and V91) detected both by Kaluzny et al. (1999b) and in this work. We

Table 1. Elements of the RR Lyrae variables in the core of M5.

Star	X[″]	Y[″]	Period	Star	X[″]	Y[″]	Period	Star	X[″]	Y[″]	Period
V4	−12.3	+73.8	0.450999	V80	−48.6	+111.6	0.336691	V114	+29.7	−2.6	0.604015
V5	−7.8	+51.6	0.546416	V81	−72.2	−121.7	0.556798	V115	+46.2	+4.9	0.614249
V6	+27.2	−46.6	0.547204	V82	−67.8	+12.4	0.558208	V116	+46.0	−2.3	0.347421
V13	+11.0	−65.4	0.512984	V87	+122.0	−1.8	0.742259	V117	+24.9	+2.8	0.335578
V14	−145.6	+103.7	0.486850	V88	+65.2	+61.8	0.327669	V118	+20.0	+7.6	0.580965
V16	+91.0	+83.9	0.647695	V89	+60.0	+64.7	0.559149	V119	+12.3	+15.6	0.551128
V24	−46.8	−71.7	0.478513	V91	−36.0	+35.0	0.585423	V123	−0.7	+28.6	0.601801
V26	+21.8	+101.5	0.623978	V93	+44.0	−35.7	0.552875	V127	−37.1	+9.2	0.544965
V27	−6.7	−59.2	0.471333	V94	−23.5	+17.4	0.533101	V128	−36.5	−8.9	0.305704
V33	−21.1	+127.5	0.501980	V95	−47.2	+102.8	0.290975	V129	−84.2	−88.1	0.553881
V34	+84.3	+59.5	0.567632	V96	−12.4	+32.9	0.511861	V130	+77.8	+57.4	0.327450
V35	−12.2	−114.7	0.308402	V97	+48.9	−92.5	0.545176	V131	+78.1	+54.9	0.281489
V38	−44.2	+117.2	0.470430	V98	+37.8	+20.0	0.306085	V133	+107.3	+43.7	0.294905
V44	−102.5	+31.1	0.329585	V99	+34.4	−0.1	0.321359	V135	−7.5	−50.9	0.627740
V45	−116.7	+65.7	0.617091	V100	+2.8	+48.7	0.294395	V137	+45.1	+40.1	0.615718
V47	−75.3	+58.1	0.540381	V103	+20.5	−8.8	0.567138	V139	−18.2	+31.9	0.300501
V52	+107.9	+35.3	0.501906	V104	−10.2	+42.1	0.310930	V160	−49.6	−42.4	0.089767
V54	+30.3	+57.2	0.453850	V109	+19.2	+1.5	0.472582	V161	+4.9	+51.6	0.331570
V56	−68.9	+96.5	0.533973	V110	+23.8	+16.4	0.598528	V162	−44.6	+15.3	0.557468
V57	−30.6	+99.7	0.284739	V112	+28.7	−31.4	0.537907	V163	−26.2	+44.1	0.600853
V60	−109.7	+8.2	0.285274								

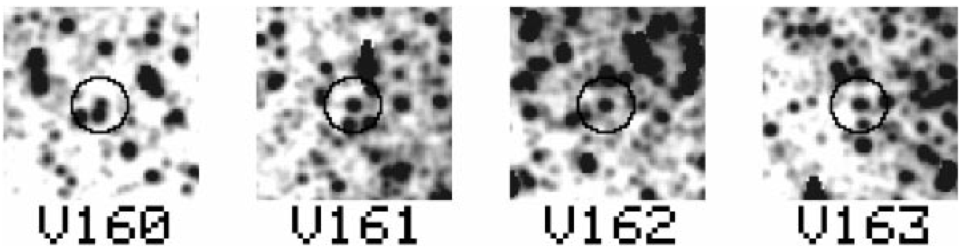

Figure 2. Finder charts for the four newly discovered variables. Each chart is 30 arcsec on a side, with east up and north to the left.

show the DOPHOT photometry and the ISM photometry in the first and the second panel respectively. One can clearly see that the measurements on the right side of Fig. 3 are much more accurate than the ones on the left side. For an objective comparison, we fitted all of these curves with a Fourier sine series in the form:

$$\text{brightness} = A_0 + \sum_{j=1}^{8} A_j \cdot \sin(j\omega t + \phi_j) \qquad (1)$$

where $\omega = 2\pi/P$ and P is the pulsation period of the star and calculated the relative errors of A_j. These quantities are presented in Table 2. It is clear that the relative errors are much smaller using the ISM. The result is most striking for V91 where the relative errors of IMS are $\sim$ 11 times smaller than the errors produced by DOPHOT. The smallest differences of the relative errors between these two methods are noted for V54 but still the light curve of this star obtained by IMS has considerably smaller scatter than the light curve obtained with DOPHOT. The light curve of V27 shows behaviour common among RR Lyr variables detected in this work. It has larger scatter of the observational points around maxima than around minima. There are three factors contributing to the effect. First, many RR Lyr found in this search are saturated near maxima, at least in some frames. Saturated pixels are rejected in the PSF fit and convolution through renormalization, nevertheless convolution is non-local and the spreading of defects cannot be eliminated completely. The saturated pixels are simply rejected in the DOPHOT reductions. The second factor comes from imperfect phasing of the light curves, which manifests itself more strongly near maxima, where light variations are steep. And the third factor comes from the Blazhko effect which usually results in a larger scatter at maximum light than at minimum light.

Additionally knowing the minimal and maximal magnitudes of these variables we transformed the light curves obtained by ISM into the relative magnitudes and then again computed the Fourier fit in form presented in (1). Next we computed the deviation parameter defined as:

$$\Delta = \frac{1}{N} \cdot \sum_{i=1}^{N} |\text{mag}(\text{jd}_i) - \text{brightness}(\text{jd}_i)| \qquad (2)$$

where N is the number of observations, mag(jd$_i$) is the relative magnitude at given HJD and brightness(jd$_i$) is the magnitude of the star for the same HJD computed from (1).

The Δ parameter is given for each star in the last column of Table 2. It is clear that the ISM photometry of variables V27 and V54 is about two times better than the DOPHOT photometry, and the improvement for variable V91 is as large as a factor of 4.3.

3.2 Variable V104

The variable V104 was classified by Drissen & Shara (1998) as an eclipsing binary star. Indeed the *HST* light curve of this star shows two clear bumps with different amplitudes and a period of slightly more than 12 hours, behaviour suggestive of a W UMa star.

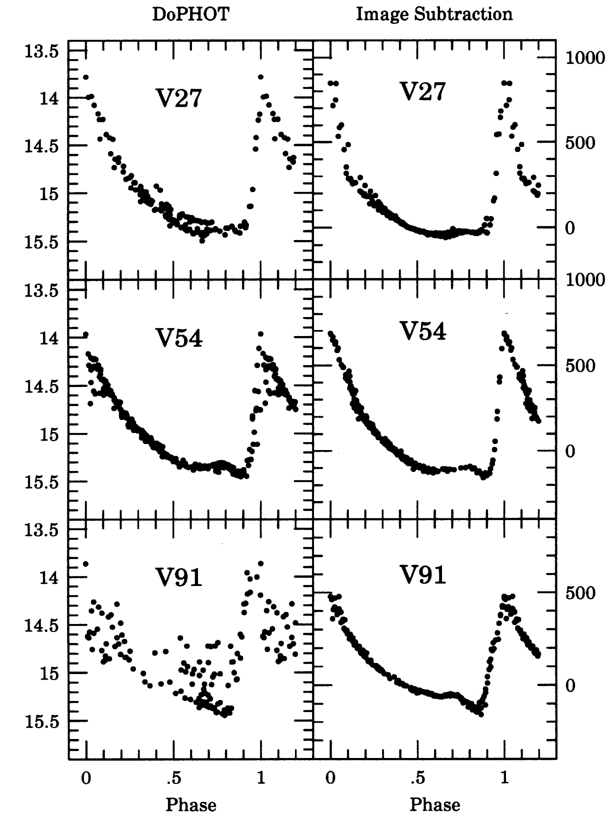

Figure 3. A comparison of light curves obtained by Kaluzny et al. (1999b) using DOPHOT software and in this work by the ISM.

Table 2. Fourier elements of the three RR Lyrae variables in the core of M5. The comparison of the relative errors of the light curves obtained by ISM and DOPHOT.

Star	$\frac{\Delta A_1}{A_1}$	$\frac{\Delta A_2}{A_2}$	$\frac{\Delta A_3}{A_3}$	$\frac{\Delta A_4}{A_4}$	Δ
V27 ISM	0.006	0.009	0.011	0.014	0.031
V27 DOPHOT	0.018	0.036	0.053	0.082	0.050
V54 ISM	0.013	0.024	0.032	0.046	0.023
V54 DOPHOT	0.007	0.015	0.021	0.033	0.043
V91 ISM	0.009	0.017	0.026	0.045	0.036
V91 DOPHOT	0.086	0.152	0.277	0.243	0.155

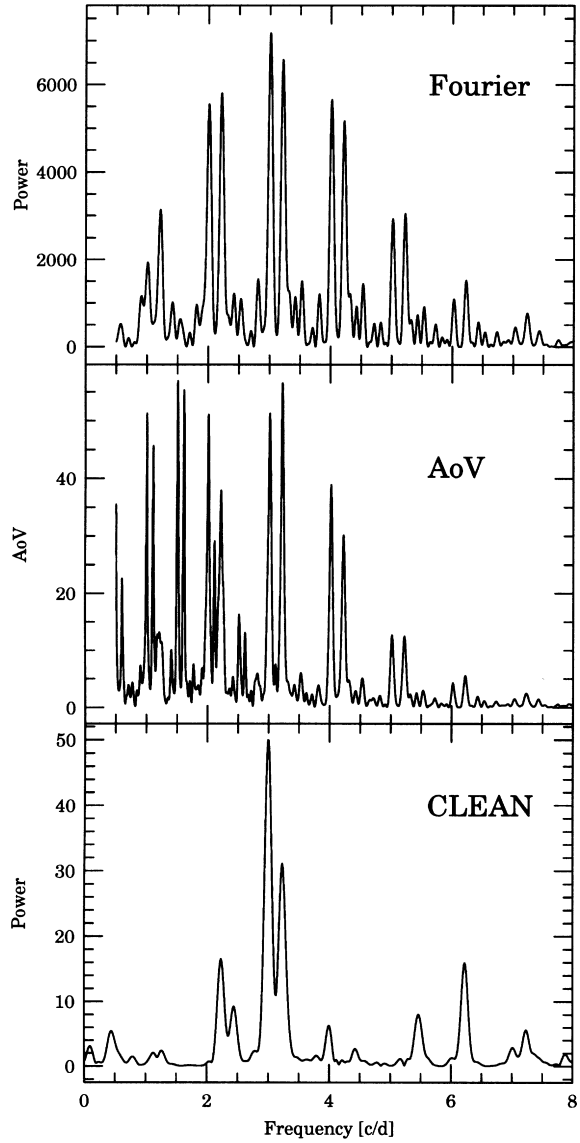

Figure 4. Fourier, AoV and CLEAN power spectra of the light curve of V104 showing the multiperiodic behaviour of this star.

Caputo et al. (1999) also suggested that this star is an eclipsing binary and found a period around 0.741 d. However, from their fig. 2 one can see that *V* the magnitude of this star is around 15.0 with $B - V = 0.4$. These properties place this star inside the area occupied by RR Lyr stars on the colour–magnitude diagram.

Our Fig. 1 shows a completely different light curve of this variable. We phased the observations with a period of 0.31093 d (typical of RRc stars) but one can clearly see large systematic departures from strict periodicity. This strongly suggests that this star is multiperiodic. Periodograms calculated with Fourier, AoV and CLEAN software are presented in Fig. 4, and confirm our hypothesis. There are two clear peaks in each periodogram in this figure, one at 3.012*c*/*d* ($P = 0.332$ d) and the second at 3.217*c*/*d* ($P = 0.311$ d). Only one of these periods can correspond to the first overtone radial pulsations. The second one is most likely connected with non-radial pulsation – behaviour seen before only in three RRc stars in M55 (Olech et al. 1999).

4 CONCLUSIONS

We have presented CCD photometry of 61 variables from the core of the globular cluster M5 based on the newly developed method of image subtraction (Alard & Lupton 1998; Alard 1999b). We have demonstrated that this method works very well even in the densest regions of the cluster. The number of variables detected in the same field using DOPHOT photometry measured from the same data set was over two times smaller. In addition, the relative errors of the Fourier coefficients of the light curves measured with DOPHOT are up to 20 times larger than the errors produced by the ISM. We conclude that the new method is very promising for searches of variable stars in globular clusters and in the near future should return numerous new discoveries plus very accurate relative photometry from ground-based data, even with medium-sized telescopes delivering moderate seeing. Image subtraction is best suited for projects for which the knowledge of the zero point is not critical, i.e. determination of periods. On the other hand it will not underperform DOPHOT in a sense that we may supplement accurate difference photometry with less accurate zero points obtained with traditional tools.

Four of our variables were previously unknown. One of them is a SX Phe star with period of 0.089767 d, one is a Bailey type RRc star, and the other two are Bailey-type RRab stars.

We have found that the variable V104, previously classified as an eclipsing variable, is an RRc Lyr star pulsating with two periods. We have concluded that owing to the close proximity of these periods only one of them corresponds to the first overtone radial pulsations and the second one is caused by non-radial pulsations. Non-radial pulsations are common among δ Scuti stars (the main-sequence variables lying in the main instability strip) but are rare among RR Lyr stars. Only three such stars were known before, all of them RRc variables in M55 (Olech et al. 1999).

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