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 20 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 HST. 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: RR Lyr - stars: variables – 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 and Shara (1998), Kaluzny et al. (1999a, 1999b) and Caputo et al. (1999).

Crowding effects make it very difficult to obtain reliable photometry of variables stars located near the central regions of globular clusters. One solution is to use the Hubble Space Telescope (HST). Drissen and Shara (1998) observed a 70" × 70" field located in the center of M5, detecting 29 variables during a 12 hr 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 and 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 kernel. Alard (1999b) modified the code of Alard and 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 and Szymański 1998) and obtained much better light curves of the microlensing events than those measured using traditional methods such as DoPHOT software (Schechter et al., 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 analyzing V-band CCD photometry of M5 taken in May and June of 1997 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 favorable 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′ × 4.4′ of the central part of M5. This field contains 26 variables which were detected by Kaluzny et al. (1999b).

Our data set is somewhat smaller than used by Kaluzny et al. (1999b), only observations taken in May and June 1997 analyzed for a total of 161 frames.
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 done with the IRAF package. The next important step is the registration of all frames onto a common pixel grid. This was 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 pix 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 onto 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 and 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 and Lupton (1998). Small PSF gradients are taken into account by subdividing each frame.

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 cutoff of 4 sigma for the detection of a candidate variable.

The actual profile photometry on individual difference images is done using the PSF for the reference image convolved with the best fit PSF matching kernel for each test image. We modeled the first order spatial variation of the PSF in the reference image using the code written for the DENIS survey (Alard 1999, 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 due to the combined effects of a slight nonlinearity at the level of 4% 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 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 center of the cluster.

In the 4.1′ × 4.1′ 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 onto a common numbering scheme. Four of our variables are new discoveries, and are labeled 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.

### 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  | $\Delta A_1$ | $\Delta A_2$ | $\Delta A_3$ | $\Delta A_4$ | $\Delta A_5$ | $\Delta A_6$ | $\Delta A_7$ | $\Delta A_8$ | $\Delta \Delta$ |
|-------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| 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        |

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 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:

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

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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 the most striking for V91 where the relative errors of IMS are \( \sim 20 \) 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 behavior common among RR Lyr variables detected in this work. It has larger scatter of the observational points around maxima than around minima. There are two 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 nonlocal 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.

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:

\[
\Delta = \frac{1}{N} \sum_{i=1}^{N} \left| \text{mag}(jd_i) - \text{brightness}(jd_i) \right|
\]

(2)

where \( N \) is the number of observations, \( \text{mag}(jd_i) \) is the relative magnitude at given HJD and \( \text{brightness}(jd_i) \) is the magnitude of the star for the same HJD computed from (1).

The \( \Delta \) 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 and 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, behavior suggestive of a W UMa 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 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 color 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 (Schwarzenberg-Czerny 1997) and CLEAN (Roberts et al, 1987) software are presented in Fig. 4, and confirm our hypothesis. There are two clear peaks in each periodogram in this figure, one at 3.012d/d \((P=0.332\,\text{d})\) and the second at 3.217d/d \((P=0.311\,\text{d})\). Only one of these periods can correspond to the 1st overtone radial pulsations. The second one is most likely connected with non-radial pulsation – behavior seen before only in three RRc stars in M55 (Olech et al. 1999).
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 δ Scuti 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 due to the close proximity of these periods only one of them corresponds to the 1st 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 laying in the main instability strip) but are rare among RR Lyr stars. Only 3 such stars were known before, all of them RRc variables in M55 (Olech et al. 1999).

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Fig. 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.
Fig. 1 Continued.
Fig. 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.
Fig. 3  A comparison of light curves obtained by Kaluzny et al. 1999b using DoPHOT software and in this work by the ISM.
Fig. 4  Fourier, AoV and CLEAN power spectra of the light curve of V104 showing the multiperiodic behavior of this star.