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**NEW VARIABLES IN M5 (NGC 5904)  
AND SOME IDENTIFICATION CORRECTIONS**

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## 1 Introduction

The bright globular cluster M5 (NGC 5904) has been the subject of many variable star searches for more than a hundred years. The first variables were discovered by Solon I. Bailey with the 13-inch Boyden Telescope at the Arequipa station in 1896 (see Pickering 1896 and Bailey 1899). The catalogue of variable stars in globular clusters (CVSGC; Clement et al. 2001) lists 169 variables, mostly of the RR Lyrae type, with 5 SX Phe stars, one W Virginis star (CW), one RV Tau, one (possibly two) eclipsing binaries, and one U Gem type star. However, there are also a number of uncertain classifications and some variables have an unknown type, or it is not even clear if they are truly variable. A new study of the variable stars in M5 is therefore pertinent.

As part of our program of CCD time-series observations of variable star populations in globular clusters (GC), we performed CCD *V* and *I* photometry of the globular cluster M5. Difference image analysis (DIA) has proven to be very efficient in identifying variable stars even in the crowded central regions of GCs (e.g. Arellano Ferro et al. 2013 and references therein). Exploration of our collection of light curves of all stars in the field of our images down to  $V \sim 18.5$  mag allowed us to identify twelve variables not previously detected; one SX Phe and eleven semi-regular variables (SR). In the present note, we report on their identifications, equatorial coordinates, ephemerides, and light curves. We argue that the known variable V155, previously classified as RRc, is in fact a contact eclipsing binary or EW. Furthermore, we have explored the light curves of a group of stars whose variability has not been confirmed and that are marked as probable non-variables in the CVSGC. Finally, we offer detailed identifications for some of the known variables in crowded regions that were misidentified in previous studies. We shall also address the cases of the cataclysmic variable or U Gem type V101 and of the variable blue straggler V159.

## 2 Observations and reductions

The observations were acquired on 11 nights between 29 February 2012 and 9 April 2014 with the 2.0m telescope of the Hanle Observatory, India. A total of 385 and 384 images in  $V$  and  $I$ , respectively, were obtained. Image data were calibrated using bias and flat-field correction procedures. We used DIA to extract high-precision time-series photometry employing the **DanDIA** pipeline for the data reduction process (Bramich et al. 2013), which includes an algorithm that models the convolution kernel matching the PSF of a pair of images of the same field as a discrete pixel array (Bramich 2008). We have also applied a post-calibration method developed by Bramich & Freudling (2012) which determines appropriate per-image magnitude offsets to correct for errors in the fitted value of the photometric scale factor  $p$ . We derived offsets of the order of  $\sim 0.02$  and  $\sim 0.03$  mag in  $V$  and  $I$ , respectively. The instrumental magnitudes are calculated via the difference flux, the reference flux and the photometric scale factor by the equation;

$$m_{\text{ins}}(t) = 25.0 - 2.5 \log \left[ f_{\text{ref}} + \frac{f_{\text{diff}}(t)}{p(t)} \right]. \quad (1)$$

The difference fluxes  $f_{\text{diff}}$  are measured by scaling the known PSF to the difference images at the position of each star. Since the constant stars have been fully subtracted in the difference images, the difference fluxes for the variables are very precise. The reference fluxes  $f_{\text{ref}}$  are, however, measured on the reference image by PSF fitting and they have the potential to suffer from the usual problems caused by blending. For the variables in the most crowded parts of the reference image, where the probability of blending is high, the brightness of a variable star may be overestimated, and its amplitude underestimated (see Section 2.3 of Bramich et al. 2011 for a more in-depth discussion of the caveats of DIA).

The instrumental magnitudes were transformed to the standard Johnson-Kron-Cousins magnitudes using secondary photometric standards in the field of view (FoV) from Stetson (2000) covering the full range of colours.

All of our  $VI$  photometry for the stars discussed in this paper is provided in Table 1. Just a small portion of this table is given in the printed version of this paper, while the full table is only available in electronic form.

## 3 Exploration of suspected non-variables in the CVSGC

In the CVSGC there are 23 stars classified as (probably) non-variables or ‘‘constant’’ (CST, CST? or ?); these are V22, V23, V46, V48, V49, V51, V124, V136, V138, V140, V141, V143-V154. Except for V22 and V141, which are outside of the FoV of our images, we have  $VI$  light curves for all of them. We have carried out a quick exploration of the light curves to comment on their possible variability or otherwise.

Firstly we have identified the 21 stars in our FoV on the colour-magnitude diagram (CMD) of Fig. 1 and the RMS diagram of Fig. 2. All of them are marked with red squares. In the RMS diagram we draw an arbitrarily set line above which all variables seem to fall and hence it can serve as a guide of detectability when judging the variability of a given candidate. While true variables are expected to have significantly larger rms values than this upper limit, we note however that non-true variables may lie above that limit if they are near a true variable due to flux contamination (e.g. V140, see below), or that true variables may be found below that limit, particularly those of very small amplitude (e.g. the SX Phe star V164). Thus, individual explorations of the light curves of specific

Table 1: Time-series  $V$  and  $I$  photometry for all stars discussed in this paper. The standard  $M_{\text{std}}$  and instrumental  $m_{\text{ins}}$  magnitudes are listed in columns 4 and 5, respectively, corresponding to the variable star in column 1. Filter and epoch of mid-exposure are listed in columns 2 and 3, respectively. The uncertainty on  $m_{\text{ins}}$  is listed in column 6, which also corresponds to the uncertainty on  $M_{\text{std}}$ . For completeness, we also list the quantities  $f_{\text{ref}}$ ,  $f_{\text{diff}}$  and  $p$  from Eq. 1 in columns 7, 9 and 11, along with the uncertainties  $\sigma_{\text{ref}}$  and  $\sigma_{\text{diff}}$  in columns 8 and 10. This is an extract from the full table, which is available with the electronic version of the article (6137-t1.txt).

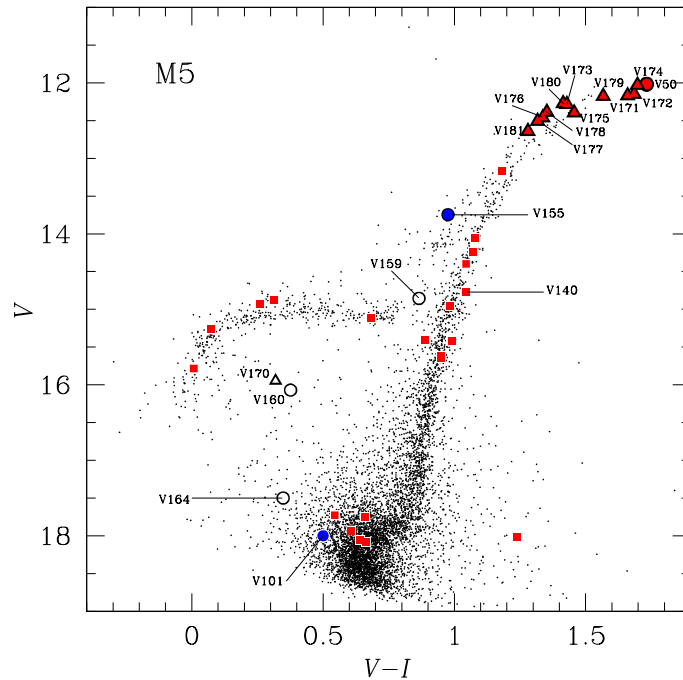
| Variable Star ID | Filter | HJD (d)       | $M_{\text{std}}$ (mag) | $m_{\text{ins}}$ (mag) | $\sigma_m$ (mag) | $f_{\text{ref}}$ (ADU s $^{-1}$ ) | $\sigma_{\text{ref}}$ (ADU s $^{-1}$ ) | $f_{\text{diff}}$ (ADU s $^{-1}$ ) | $\sigma_{\text{diff}}$ (ADU s $^{-1}$ ) | $p$    |
|------------------|--------|---------------|------------------------|------------------------|------------------|-----------------------------------|--|------------------------------------|---|--------|
| V23              | V      | 2455987.37467 | 14.402                 | 15.567                 | 0.002            | 5984.932                          | 11.137                                 | -51.549                            | 9.416                                   | 1.0195 |
| V23              | V      | 2455987.37903 | 14.404                 | 15.569                 | 0.002            | 5984.932                          | 11.137                                 | -59.403                            | 9.521                                   | 0.9697 |
| :                | :      | :             | :                      | :                      | :                | :                                 | :                                      | :                                  | :                                       | :      |
| V23              | I      | 2455987.37248 | 13.353                 | 14.622                 | 0.002            | 14205.530                         | 25.101                                 | -44.978                            | 27.407                                  | 1.0588 |
| V23              | I      | 2455987.37686 | 13.370                 | 14.639                 | 0.002            | 14205.530                         | 25.101                                 | -278.790                           | 30.268                                  | 1.0423 |
| :                | :      | :             | :                      | :                      | :                | :                                 | :                                      | :                                  | :                                       | :      |
| V25              | V      | 2455987.37467 | 14.632                 | 15.826                 | 0.003            | 2449.232                          | 15.883                                 | +2267.438                          | 12.352                                  | 1.0195 |
| V25              | V      | 2455987.37903 | 14.625                 | 15.819                 | 0.003            | 2449.232                          | 15.883                                 | +2186.565                          | 11.576                                  | 0.9697 |
| :                | :      | :             | :                      | :                      | :                | :                                 | :                                      | :                                  | :                                       | :      |
| V25              | I      | 2455987.37248 | 14.253                 | 15.542                 | 0.004            | 3901.695                          | 29.242                                 | +2298.204                          | 26.254                                  | 1.0588 |
| V25              | I      | 2455987.37686 | 14.310                 | 15.599                 | 0.005            | 3901.695                          | 29.242                                 | +1939.003                          | 29.961                                  | 1.0423 |
| :                | :      | :             | :                      | :                      | :                | :                                 | :                                      | :                                  | :                                       | :      |

cases are required. In Table 2 we list the mean magnitudes and rms values in the  $V$  light curves. In the last column we list the value of the upper limit rms corresponding to the mean magnitude. Except for V140, all the stars listed above fall below the threshold. From the individual explorations we found that V140 does in fact show some variations. However we argue that these are due to flux contamination by a nearby variable (V175) as it will be discussed in § 5. For the rest, we found no signs of variability confirming their classification as non-variables (or CST) in the CVSGC.

#### 4 Comments, identification and classification correction for some previously known variables

During the process of variable star identification we noticed that stars V25, V36, V53, V74, V102 and V108 are all very close to a neighbour of similar brightness or much brighter. While checking the finding charts of the discovery papers, we found that their identifications are dubious or definitely wrong, mainly due to the fact that the stars are not resolved in old plates and/or that they are close to the cluster central regions. Here we offer a precise identification and a few comments on each variable. We have confirmed the variable nature of these stars by phasing the light curves of the two candidates and by blinking the difference images. It was also noted that the equatorial coordinates in the CVSGC of the variable V140 point to a non-variable star. We address the cases of V50 whose variability has not been clearly established and of V155 that needs a reclassification. To avoid confusion in future work we include here in Table 3 the correct equatorial coordinates of all these stars. Below we offer a brief comment on individual stars including the U Gem type star V101, and binary V159.

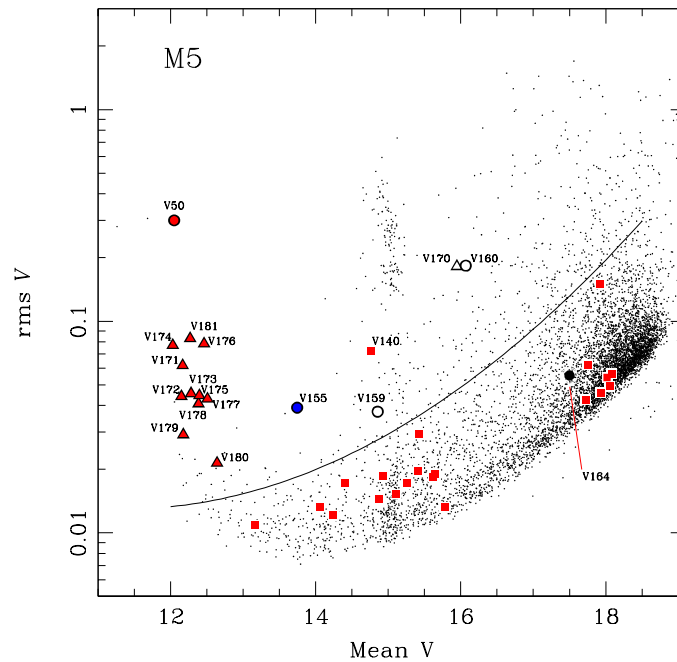
V25 is a very close pair that in our images is heavily blended. In the finding chart of the discovery paper (Bailey 1902), the star looks like a single one. Careful blinking of the difference images makes it clear that the true variable is the western star of the pair, as



**Figure 1.** Colour-magnitude diagram of M5 with the new variables marked with triangles. The colour code is: empty symbols for blue straggler variables, the position of binary V159 is biased since it is heavily blended; red triangles for tip of the RGB variables; blue filled circles for two previously known variables V101 and V155. The cataclysmic variable V101 is plotted at its approximate position during outburst. No other known variables are shown. Red squares are stars listed as variables but whose variability has not been confirmed. See the text for a detailed discussion.

Table 2: Mean magnitudes and rms for stars whose variability is not confirmed. Local rms refers to the upper limit of the main rms distribution for a given value of  $\langle V \rangle$ , represented by the continuous line in Fig. 2.

| Var ID | $\langle V \rangle$ | rms $V$ | local rms | Var ID | $\langle V \rangle$ | rms $V$ | local rms |
|--------|---------------------|---------|-----------|--------|---------------------|---------|-----------|
| V23    | 14.40               | 0.017   | 0.023     | V145   | 15.26               | 0.017   | 0.033     |
| V46    | 17.93               | 0.150   | 0.184     | V146   | 15.65               | 0.019   | 0.040     |
| V48    | 14.24               | 0.012   | 0.022     | V147   | 15.12               | 0.015   | 0.031     |
| V49    | 15.78               | 0.013   | 0.043     | V148   | 15.62               | 0.018   | 0.040     |
| V51    | 14.06               | 0.013   | 0.020     | V149   | 17.75               | 0.062   | 0.160     |
| V124   | 14.88               | 0.015   | 0.028     | V150   | 18.08               | 0.056   | 0.208     |
| V136   | 14.93               | 0.018   | 0.028     | V151   | 18.02               | 0.054   | 0.198     |
| V138   | 13.17               | 0.011   | 0.016     | V152   | 17.72               | 0.043   | 0.160     |
| V140   | 14.76               | 0.072   | 0.028     | V153   | 18.05               | 0.049   | 0.203     |
| V143   | 15.42               | 0.029   | 0.036     | V154   | 17.93               | 0.046   | 0.184     |
| V144   | 15.41               | 0.020   | 0.036     |        |                     |         |           |



**Figure 2.** The rms  $V$  magnitude deviations calculated for 8431 stars in our FoV of M5 as a function of mean magnitude  $V$ . The sybols and colour code are as in Fig 1. The continuous line represents an arbitrary threshold for variability detectability (see text in § 3).

identified in Fig. 4.

V36 is also called V135 (see CVSGC for M5, 2014 update). The star is incorrectly identified in the chart of Caputo et al. (1999), labelled as V135, as the south-western star of the pair. The RRab variable is actually the north-eastern and brighter star of the pair.

V50 sits on the tip of the RGB. Bailey (1917) suggested a period of 106 d that was not confirmed by Oosterhoff (1941) who described the variation as irregular. Our data suggest a period of 107.6 d, in good agreement with Bailey's result. Therefore we classify the star as a semi-regular late-type variable (SRA). Its light curve, phased with the above period, is shown in Fig. 3.

V53 is not resolved in the finding chart of Bailey (1902) and not identified afterwards. The correct variable is the eastern star of the pair.

V74 is not resolved in the finding chart of Bailey (1902) and not identified afterwards. The correct variable is the western star of the pair.

V101 is a cataclysmic variable of the U Gem type. It was discovered by Oosterhoff (1941) who classified it as SS Cyg (or dwarf nova). Two outbursts of amplitude 2.7 mag within 100 days in the  $V$  light curve were detected by Kaluzny et al. (1999) who argue in favour of a short duty cycle with a characteristic time of about 3.4 hours. Our  $VI$  light curves, displayed in the mosaic of Fig. 3, span 770 days and two outbursts are clearly seen at HJD 2456029.4 and 2456312.5 d reaching 18.5 and 18.0 mag in  $V$ , and 18.0 and 17.0 mag in  $I$  respectively.

V102 The identification chart in Oosterhoff (1941) shows a strong blend close to the saturated central region that prevents an accurate identification. The authentic variable is the SE star of the pair.

V108 The variability of this star was announced by Kadla et al. (1987) (see also

Gerashchenko 1987). It was identified by Drissen & Shara (1998) in their *Hubble Space Telescope (HST)* image but mistakenly labelled as V22. The identification of the star by Caputo et al. (1999), now labelled as V108, points to the wrong star to the east of the real variable. We confirm that the variable star is the western star of the pair, in agreement with Drissen & Shara's (1998) identification.

Table 3: Known variables with corrected classifications, equatorial coordinates and identifications in Fig. 4.

| Var ID | Variable type | RA(J2000.0) | Dec.(J2000.0) |
|--------|---------------|-------------|---------------|
| V25    | RRab          | 15 18 30.98 | +02 02 42.5   |
| V36    | RRab          | 15 18 32.66 | +02 03 58.9   |
| V50    | SRA           | 15 18 36.04 | +02 06 37.8   |
| V53    | RRc           | 15 18 37.92 | +02 05 06.8   |
| V74    | RRab          | 15 18 47.19 | +02 07 25.7   |
| V101   | U Gem         | 15 18 14.51 | +02 05 35.7   |
| V102   | RRab          | 15 18 34.37 | +02 04 34.4   |
| V108   | RRc           | 15 18 33.79 | +02 04 47.0   |
| V140   | CST           | 15 18 36.18 | +02 05 13.2   |
| V155   | EW            | 15 18 33.40 | +02 05 12.2   |
| V159   | E             | 15 18 32.88 | +02 04 36.5   |

V140 is identified by Caputo et al. (1999) but the equatorial coordinates given in the CVSGC have a typo error producing some confusion in the identification and in the variable nature of the star which is classified as a probable non-variable. The star pointed to by the CVSGC at 15:18:36.18; +02:03:13.1 is not variable. The correct coordinates of the star identified by Caputo et al. (1999) are given in Table 3. However, this V140 is very close to a much brighter star and a careful blinking of the difference images clearly reveals that the authentic variable is the brighter star, which we have identified as the new SRA variable V175 (see §5). Both the light curves for V140 and V175 are shown in the mosaic of Fig. 3. The light curve of V140 has been contaminated by the real variations in the much brighter star V175. We conclude that V140 is not a variable star while V175 is an SRA variable.

V155 was discovered by Drissen & Shara (1998) and they classified it as RRc. However, the star lies near the RGB on the CMD (see Fig. 1) and the light curve in Fig. 3 is similar to that of an eclipsing binary of the EW type, or contact binary, when phased with the ephemerides  $P = 0.664865$  days and the epoch 245 6504.2067 d. Note that two different depths of the minima, particularly visible in the  $V$  light curve, are implied.

V159 is classified in the CVSGC as a probable eclipsing binary. The star was identified as variable by Drissen & Shara (1998) on their HST images and labelled as V28. The V159 name was given by Caputo et al. (1999) on their finding chart. We find that this star is highly blended in our images, which affects the star's position on the CMD. We detected two clear eclipses in the  $V$  band at JD 2455989.52 and 2456750.44, of about 0.15 mag depth (see Fig. 3). However, we are not able to determine the periodicity although we confirm the star as an eclipsing binary.

## 5 New variable stars in M5

To search for new variables in the field of M5 we have used several approaches. We isolated all stars in regions of the CMD where most variable stars in a GC tend to be found. This includes the horizontal branch, the blue stragglers region and the RGB. We identified all previously known variables in the field of our images and studied in detail the light curves of the rest of the stars. This procedure allowed us to identify a new large amplitude ( $A_V \sim 0.6$  mag) SX Phe star V170, for which we identify only one period. Then we explored the difference images for clear variations; this approach allowed us to discover the variability of six SRA (V171, V172, and V174-V177). A third approach was via the rms diagram of Fig. 2. It can be seen from this diagram that our photometry achieves uncertainties between 7 and 20 mmag at the bright end. High values of rms are generally produced by variable stars. For instance the group of stars with rms above 0.1 mag and with  $V \sim 15$  are all RR Lyrae stars which are not discussed in the present paper. Through this procedure we identified five additional SRA stars V173 and V178-V181. For some of these new SRA stars we have been able to estimate a periodicity.

The new variables, their equatorial coordinates, periods and epochs are listed in Table 4 and their position on the CMD and the rms diagram are displayed in Figs. 1 and 2 respectively. Their light curves in the  $V$  and  $I$  bands, phased whenever possible or as a function of HJD otherwise, are displayed in Fig. 3.

In the identification chart of Fig. 4, we have marked a detailed identification for all variable stars discussed in this paper. No effort has been made to identify the numerous known variables listed in the CVSGC since that will be the subject of a future paper.

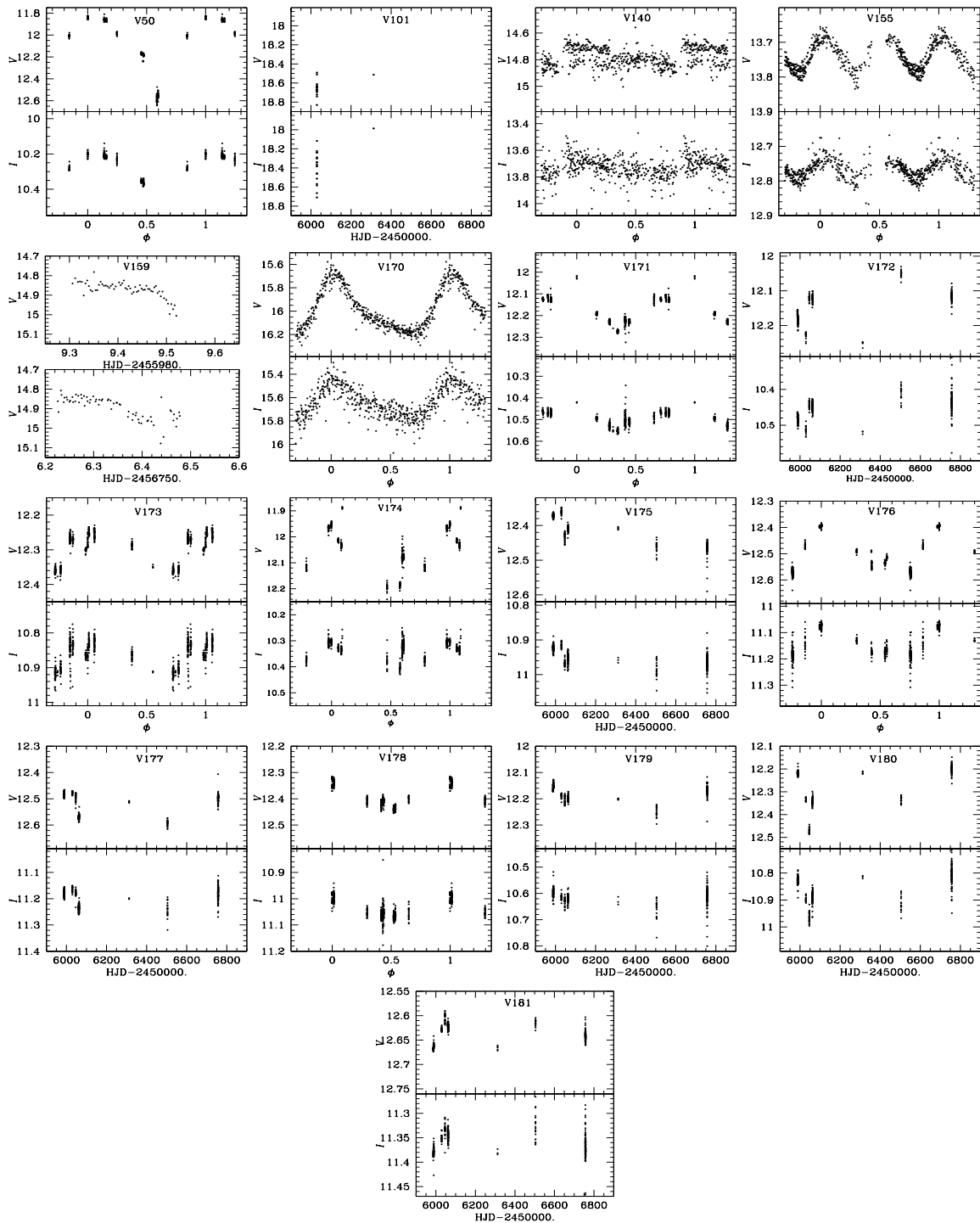
Table 4: New variable stars found in M5, V170-V181.

| Name | Variable type | RA (J2000.0) | Dec. (J2000.0) | Period days | Epoch (-245 0000.) | $\langle V \rangle$ mag | $\langle I \rangle$ mag | $A_V$ mag | $A_I$ mag |
|------|---------------|--------------|----------------|-------------|--------------------|-------------------------|-------------------------|-----------|-----------|
| V170 | SX Phe        | 15 18 32.14  | +02 04 20.4    | 0.089467    | 6063.3361          | 15.95                   | 15.63                   | 0.57      | 0.41      |
| V171 | SRA           | 15 18 34.26  | +02 04 24.2    | 28.8        | 6312.5083          | 12.17                   | 10.50                   | 0.25      | 0.14      |
| V172 | SRA           | 15 18 31.59  | +02 04 41.4    | –           | –                  | 12.15                   | 10.47                   | 0.23      | 0.13      |
| V173 | SRA           | 15 18 28.42  | +02 04 29.8    | 43.1        | 6504.1686          | 12.28                   | 10.86                   | 0.13      | 0.13      |
| V174 | SRA           | 15 18 34.18  | +02 06 25.5    | 80.6        | 6063.4183          | 12.03                   | 10.33                   | 0.33      | 0.15      |
| V175 | SRA           | 15 18 36.22  | +02 05 11.3    | –           | –                  | 12.40                   | 10.94                   | 0.18      | 0.13      |
| V176 | SRA           | 15 18 37.38  | +02 06 08.2    | 133.3       | 5989.3064          | 12.46                   | 11.13                   | 0.22      | 0.20      |
| V177 | SRA           | 15 18 41.40  | +02 06 00.9    | –           | –                  | 12.51                   | 11.19                   | 0.13      | 0.10      |
| V178 | SRA           | 15 18 33.10  | +02 04 58.0    | 141.6       | 5987.4759          | 12.39                   | 11.03                   | 0.12      | 0.10      |
| V179 | SRA           | 15 18 33.42  | +02 04 59.6    | –           | –                  | 12.18                   | 10.61                   | 0.12      | 0.11      |
| V180 | SRA           | 15 18 35.82  | +02 03 42.4    | –           | –                  | 12.27                   | 10.86                   | 0.24      | 0.24      |
| V181 | SRA           | 15 18 45.40  | +02 04 30.9    | –           | –                  | 12.64                   | 11.36                   | 0.07      | 0.08      |

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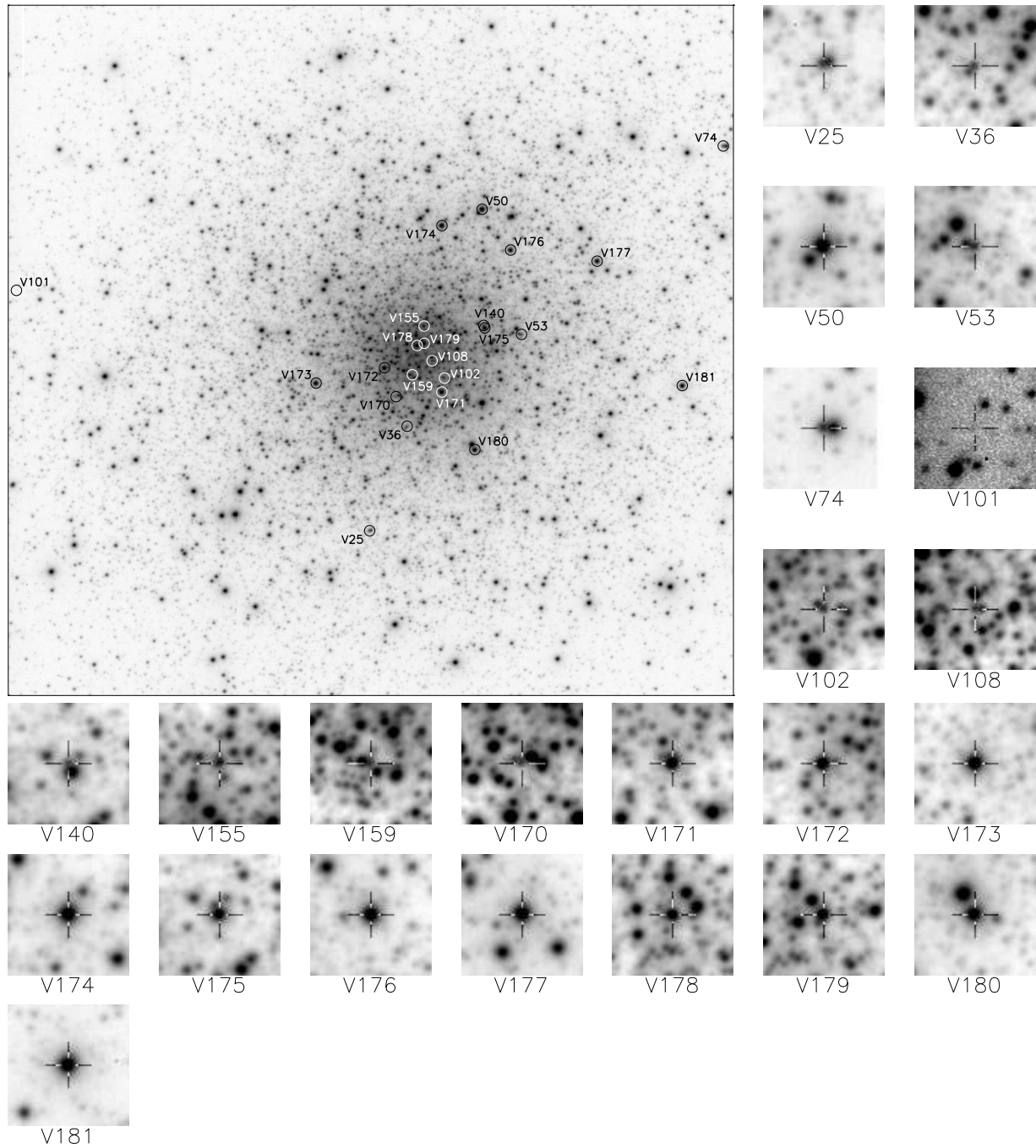
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**Figure 3.** *V* and *I* light curves of the variable stars found in this work (V170-V181). V50, V101, V140, V155 and V159 are discussed in the text. For V101 only the data during outburst are displayed. For V159 the two panels are *V* light curves during eclipses. When the period is known, light curves are phased with the ephemerides in Table 4.





**Figure 4.** Finding charts from our *V* reference image; North is up and east is to the right. The cluster image is  $8.39 \times 8.39$  arcmin<sup>2</sup> and the individual stamps are  $24.0 \times 24.0$  arcsec<sup>2</sup>.

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