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VARIABLE STARS NEAR β CAS DISCOVERED ON SCANNED PHOTOGRAPHIC PLATES AT THE STERNBERG ASTRONOMICAL INSTITUTE

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Abstract. We present results of searching for variable stars in the field of β Cassiopeiae on digitized photographic plates of the Sternberg Astronomical Institute's plate stacks. The negative astronomical plates of 30 x 30 cm size (that corresponds to 10° x 10° field of view) were obtained with the 40 cm astrograph in 1940–90s. We have discovered and investigated 1011 new variable stars and found 263 previously known variable stars. New variables include 682 eclipsing binaries of different subtypes, 5 BY Draconis stars, 5 classical Cepheids and 4 Cepheids of the Galaxy's spherical component, 3 δ Scuti stars, 15 high-amplitude δ Scuti stars (HADS), 33 RR Lyrae stars, 1 RS CVn star, 44 semi-regular red variables, 207 irregular variables (65 yellow or white stars and 142 red stars of LB type), and 12 variable stars that need confirmation and more careful study with CCD. Some of discovered stars initially were marked as suspected, for now more than 20 of them have accurate elements derived from our CCD-photometry. We considered only about 400 plates of interest from the 22500 pieces collection. So the amount of the variables "hidden" in the Sternberg Astronomical Institute's plate stacks is enormous.

1. INTRODUCTION

Astronomers in Moscow started regular photographic observations of the sky for variable-star studies in 1895. Several different telescopes were used to take direct sky plates for astrometry and for astrophysics. The Moscow plate archive now contains more than 60 000 direct photographs and objective-prism plates taken in Moscow and at other sites in Russia. The most important part of the Moscow plate collection are direct sky photographs acquired in 1948–1996 with a

40-cm astrograph. This instrument was ordered by Prof. Cuno Hoffmeister for Sonneberg Observatory (Germany) and first installed there in 1938. 1658 plates from this telescope, taken in 1938–1945, are kept in Sonneberg. In 1945, the telescope was taken to the Soviet Union as a part of the World War II reparations. It was initially installed in Simeiz (Crimea), then brought to Kuchino near Moscow, and in 1958 became the first instrument of the Crimean Laboratory of the Sternberg Institute in Nauchny, Crimea. The total number of plates taken with the 40-cm astrograph after 1948 is about 22 500. A single attempt of direct comparison between Sonneberg and Crimean plates of the 40-cm astrograph at a blink comparator was undertaken in 1980s (Samus, 1983).

The field of view of the 40-cm astrograph is $10^{\circ}\times10^{\circ}$, on 30×30 cm plates (the focal length is 1600 mm). The typical exposure time for the variable-star fields was 45 minutes. The limiting magnitude of good-quality plates is about 17.5 in B-band. The instrument was mainly used for variable-star studies, including search for new variables. For some fields, rich series of plates exist (about 500 plates). For variable stars that can be found in several fields, sometimes as many as 1000 photographic plates are available. Plates are kept in good conditions, most plates, initially of excellent quality, are still perfect.

Guaranteed conservation of the vast amounts of information contained in the plate collection and its use by means of modern methods of image processing require digitization of plate archives. This work started in Moscow, in 2004, after the purchase of two Creo EverSmart Supreme II scanners.

Most plates from the 40-cm astrograph were taken for variable-star studies. We continue this work using digital images obtained in the process of scanning the Moscow collection plates. From 2006 to 2014 we discovered 595 new variable objects (mostly variable stars, but also extragalactic objects) on scans of some selected star fields (Sokolovsky 2006, Manannikov et al. 2006, Kolesnikova et al. 2007a,b, 2008, 2010, Sokolovsky et al. 2014). We introduced preliminary designations for variable stars discovered in this program with the prefix MDV (Moscow Digital Variable).

2. SCANNING AND REDUCTION OF IMAGES

B Cassiopeiae field ($00^{h}09^{m}.2$, $\delta = +59°09'$, J2000) was photographed with the 40-cm astrograph in 1964–1994, a total of 391 plates were acquired. The description of the scanning and reduction techniques used is given by Kolesnikova et al. (2008, 2010). We present a summary for our techniques. The software controlling the scanner provides a digital RGB image in TIFF format. We converted the resulting images to the FITS format, used in astronomical applications, using a code we specially developed, tiff2fits (ftp://scan.sai.msu.ru/pub/software/tiff2fits/). In this process, we kept only the green channel of the original TIFF image, chosen empirically.

Photometric properties of a plate vary considerably across the field of view due to aberrations in the astrograph, air mass differences, and possible inhomogeneity

of the emulsion layer and the chemical processes used when developing the plate. To avoid difficulties with the photometric calibration and facilitate the astrometric reduction, we subdivided the digital images into a number of subfields, each about 0.5 square degrees in size. These subfields were reduced completely independently, and the results were merged at the last stage.

Some of the plates were taken with offsets relative to the central star of β Cas, and the shifts between plates can reach 1◦ or more. To ensure that the subfields of different plates of the series correspond to the same regions on the sky, these subfields were not introduced relative to the plate center, but instead relative to the pixel coordinates of a reference star, chosen so that it was present on all plates of the series.

We reduced each set of photographs, divided into subfields, using the VaST (http://scan.sai.msu.ru/vast) software package that we developed earlier (Sokolovsky and Lebedev 2005), which incorporates the SExtractor package (Bertin and Arnouts 1996). We use SExtractor to detect stars in our images, and determine their pixel coordinates and instrumental magnitudes. A star's brightness was measured using a round aperture, whose size was selected according to the apparent sizes of the stars in the image. VaST launches SExtractor for the reduction of each digitized image, cross-identifies stars measured on different plates, and enables absolute calibrations of photometric and astrometric images.

To identify the stars found in an image with stars in the reference image, the VaST code derives a linear transformation between the systems of pixel coordinates for the two images.

We then related the magnitude scale for the identified image to the instrumental scale of the reference image. For more information see Sokolovsky et al. (2014).

In the last reduction stage, we refered the pixel coordinates of the reference-image stars to the equatorial stellar coordinates in the USNO-B1.0 catalog (Monet et al. 2003) and performed an absolute calibration of the magnitude scale. We used the Astrometry.net (http://astrometry.net/) software (Hogg et al. 2008, Lang et al. 2010) for the astrometric reduction of our reference images.

The resulting light curves are characterized by an rms error of 0.05–0.15 mag for stars in the 13.5–16.5 mag range.

3. SEARCH FOR VARIABLE STARS

Our semi-automated variable-star search techniques are described in detail in Kolesnikova et al. (2008). The stages of the search include: (i) deriving a relationship between a star's brightness and the rms deviation between its instrumental magnitude and the magnitude on the reference plate, (ii) identifying objects with possible brightness variations, and (iii) verifying the significance of periodic or aperiodic variations for the suspected objects. The last stage was a final selection of variable stars in a non-automatic mode, which consisted of a visual inspection of the light curves.

We verified that the detected variable stars were new variables using the database of the General Catalogue of Variable Stars (Samus et al. 2007-2014), the VSX International Variable Star Index (http://www.aavso.org/vsx/) maintained by the American Association of Variable Star Observers, and the SIMBAD database (http://simbad.u-strasbg.fr/simbad/).

4. RESULTS

After revision of our list of discoveries in summer of 2014 we have 1011 new variable stars and 263 previously known variables mentioned in the General Catalog of Variable Star (GCVS) or other lists. New variables include 682 eclipsing binaries (345 Algol type binaries, 124 β Lyrae type stars and 213 W Ursa Majoris type stars), 5 BY Draconis stars, 5 classical Cepheids and 4 Cepheids of the Galaxy's spherical component, 3 δ Scuti stars, 15 high-amplitude δ Scuti stars (HADS), 33 RR Lyrae stars, 1 RS CVn star, 44 semi-regular red variables, 207 irregular variables (65 yellow or white stars and 142 red stars of LB type), and 12 variable stars that need confirmation and more careful study with CCD. The results are preliminary. Some of discovered stars initially were marked as suspected, for now more than 20 of them have accurate elements derived from our CCD-photometry.

Some examples of phased light curves are presented in Figures 1, 2 and 3.

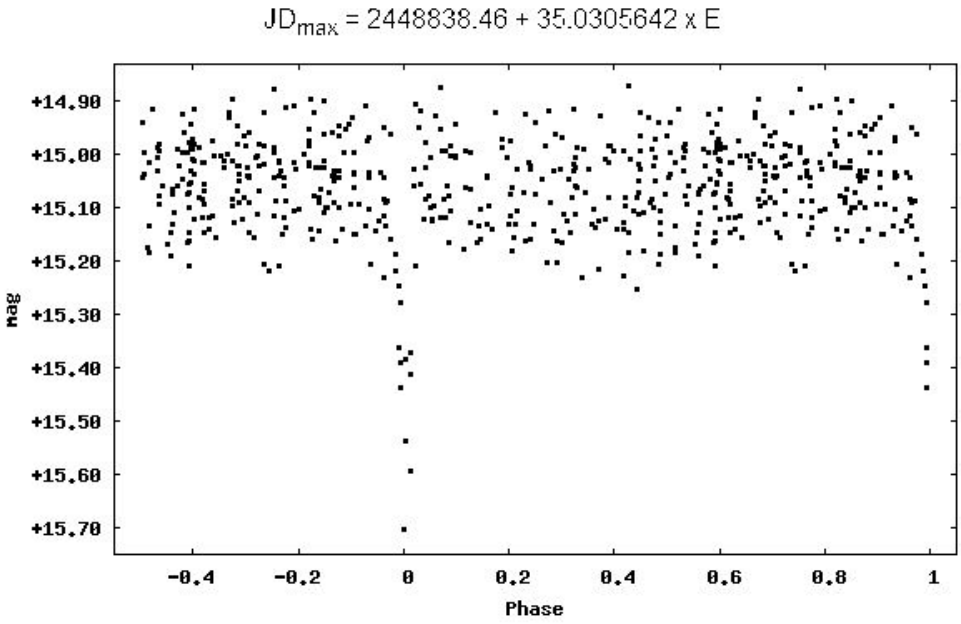

Figure 1: USNO-B1.0 1473-0013593, eclipsing binary of Algol type.

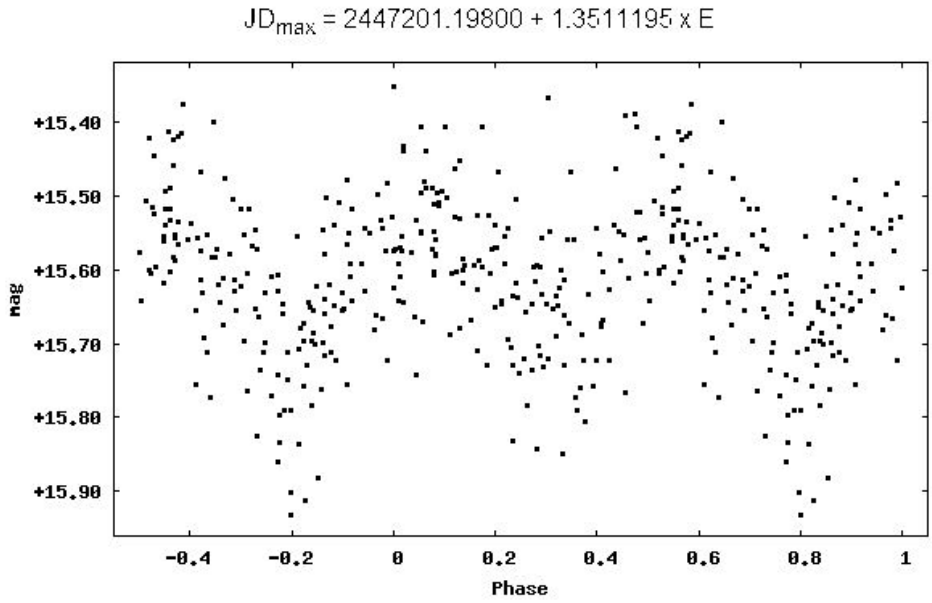

Figure 2: USNO-B1.0 1493-0392901, eclipsing binary of β Lyrae type.

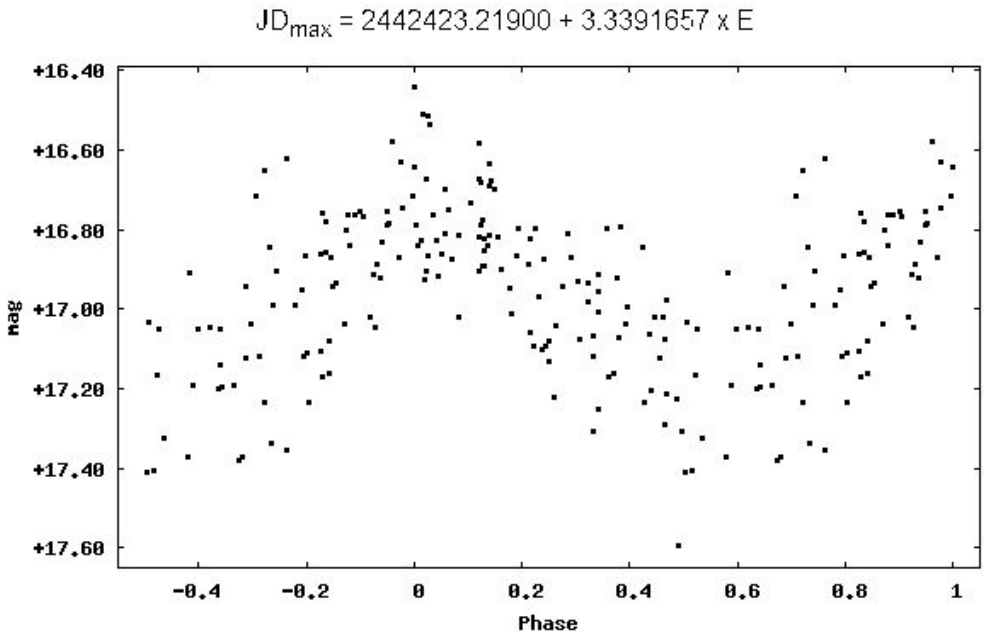

Figure 3: USNO-B1.0 1507-0011340, δ Cephei type star.

The field of β Cas has 100 square degrees which is less than 0.25 per cent of the overall sky area. We discovered 15 HADS variables here. Additionally we have two δ Scuti type stars with amplitudes of $0^m.3$ and more from GCVS. Simple extrapolation gives an expected number of HADS for all sky of more than 5000. Still, before our discoveries made with Moscow plate archive the total number of δ Scuti stars with amplitudes no less than $0^m.2$ in the GCVS was 121 only.

In the course of our study we found a bimodal HADS USNO-B1.0 1491-0020709. The star shows periods of P0 = $0^d.185785$ and P1=$0^d.244527$. The case itself is not outstanding for stars of this type in time of high time resolution CCD-photometry. But the discovery is made using photographic images with exposures of 45 minutes. Periodograms and light curves are given in Figures 4 and 5.

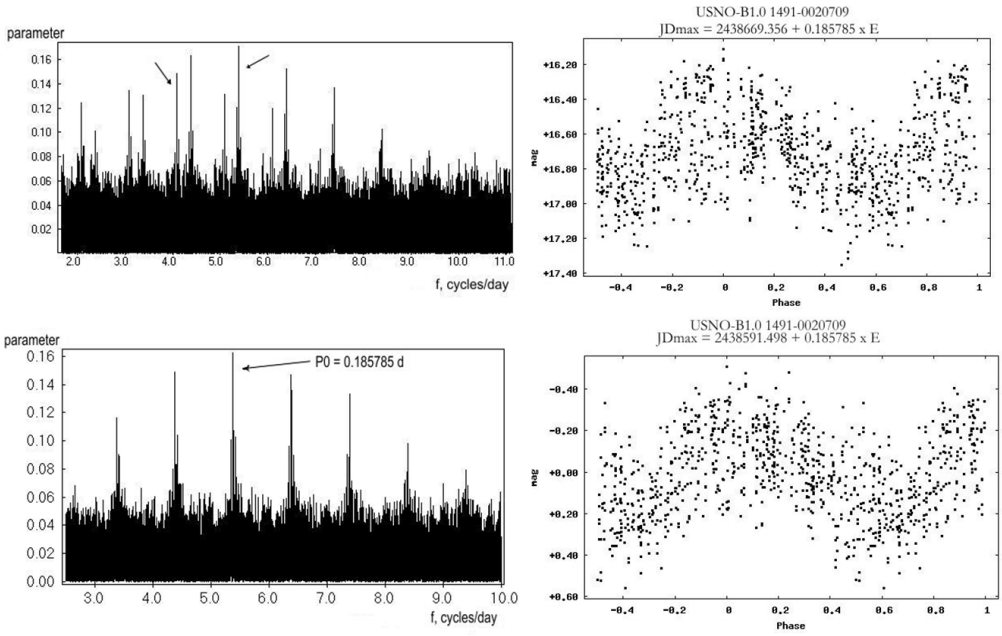

Figure 4: Periodograms (left) and phased curves (right) for USNO-B1.0 1491-0020709. The higher panel shows data for P0 = $0^d.185785$. The lower panel shows data after subtraction of P1 = $0^d.244527$.

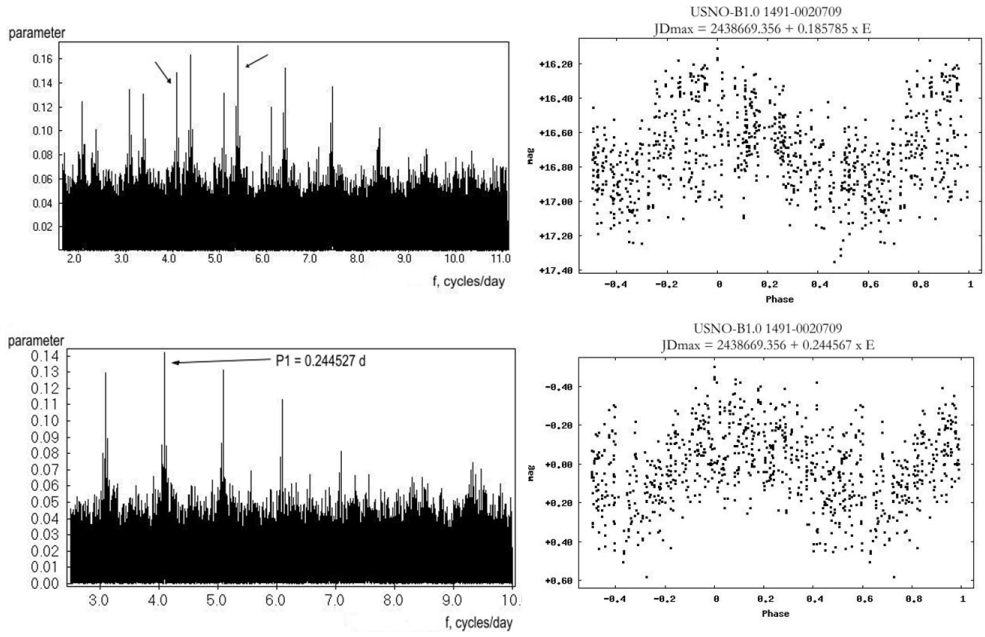

Figure 5: Periodograms (left) and phased curves (right) for USNO-B1.0 1491-0020709. The higher panel shows data for P0 = 0^d.185785. The lower panel shows data after subtraction of P0 = 0^d.185785.

5. CONCLUSIONS AND PERSPECTIVES

We have developed semi-automated techniques to digitize plates of the Moscow collection, search for variable stars on digital images and perform photographic photometry. We work to improve them and to fully automatize the process. The Sternberg Astronomical Institute's plate stacks have a lot of star fields, so we are going to continue collecting and investigating digital images of the photographic plates.

This study resulted in the discovery and investigation of 1011 new variable stars of different types. After a while we plan to publish a new part of the MDV list for β Cas field.

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