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Observations of cataclysmic variables with a 70-cm telescope

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A brief history of our efforts to make photometric investigations of cataclysmic variables using a relatively small 70-cm telescope is presented. We describe the instrumentation used for their investigations and most important results. We also analyse the reasons that allowed us to achieve new interesting results in rather middling atmospheric conditions at Kourovka Observatory.

Keywords: Instrumentation: photometers – novae, cataclysmic variables – stars: oscillations

1 Introduction

Cataclysmic variables are interacting binaries that consist of a white dwarf primary accreting matter from a low mass secondary filling its Roche lobe. The path that the transferred matter takes depends strongly on the magnetic field of the white dwarf. A bright accretion disk forms in non-magnetic systems, while matter swirling along field lines releases energy in their magnetic counterparts. According to their long-term behaviour, cataclysmic variables are subdivided into classical novae, dwarf novae and nova-like variables. By definition, nova-like variables should not display any dwarf nova outbursts. As a consequence of such a vague definition, the nova-like class is a very heterogeneous group of stars, the subclasses of which are defined by their photometric and spectroscopic behaviour (e.g., anti-dwarf novae, SW Sex stars and UX UMa stars) and the presence of magnetic fields (polars and intermediate polars). Most of cataclysmic variables in their normal brightness state are faint objects. They demand relatively large telescopes for observations. In this paper we describe the development of our observational facilities, which allowed us to successfully observe such stars, and most important results. We also analyse the reasons that allowed us to achieve these interesting results in rather middling atmospheric conditions at Kourovka Observatory.

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2 Instrumentation

Observations of cataclysmic variables at Kourovka Observatory, Ural State University, were initiated owing to the program of coordinated optical and space observations of X-ray sources that was arranged by Sternberg Astronomical Institute of Moscow State University in mid-1980s. At that time we performed observations with a simple one-channel photoelectric photometer and a computer that allowed registering photometric data directly in computer memory. However, the one-channel photometer was unable to make continuous brightness measurements of a program star during all the night because it was necessary to periodically check the stability of atmospheric transparency by measurements of a comparison star. To avoid this disadvantage, which obviously diminishes the amount of information from observations, we designed and manufactured a two-star photometer.

A complexity of most multi-channel photometers described in the literature is that the channels of the photometer must move in order to centre two stars in the diaphragms. We proposed a new design of the two-star photometer, in which the channels are immovable. The centring of two stars in the diaphragms is fulfilled by means of rotating the photometer around the optical axis of the telescope and moving two rectangular prisms attached to the slide carriage along the optical axis. Besides these prisms, the slide carriage carries another prism creating an offset field. The movable eyepiece allows a guiding star to be chosen in this offset field. Such a photometer makes it possible to maintain relative centring of two stars in the diaphragms for a long time. The design of the photometer is described in Kozhevnikov and Zakharova (2000).

At first we tried to use the two-star photometer with the 45-cm telescope AZT-3. However, manual guiding by using a guiding star turned out difficult due to imperfection of the mechanisms of precise movement, which possessed backlash. In addition, the unfavourable design of the telescope mounting did not allow us to make continuous measurements during the whole night. Therefore we modernised another telescope of Kourovka Observatory. This telescope was not in wide use due to its small diameter (25 cm). But this telescope had the perfect mechanisms of precise movement without backlash. These mechanisms, however, worked manually. We affixed step motors to these mechanisms and replaced the former tube of the telescope by a tube with a 70-cm mirror. This telescope tube was designed and manufactured at Kourovka Observatory.

In 1996–1997 the two-star photometer attached to the 70-cm telescope was used for the observations of the eclipsing binary CM Dra according to the TEP network with the goal to detect planetary transits. Due to these observations we made sure that our photometer can suppress action of unstable atmospheric transparency and light absorption by thin clouds, which are usual at Kourovka Observatory. Although other participants of the TEP network performed observations at observatories located on high mountains and used larger telescopes, our precision (0.005 mag) turned out only a bit worse than the precision of most other participants of the TEP network (0.003–0.004 mag). This follows from Table 3 in Deeg et al. (1998).

Although the step motors of the 70-cm telescope could work by using computer control, at first we performed observations by guiding manually by means of the eyepiece and a guiding star by pushing the buttons. It is clear that such guiding

remained difficult and did not allow us to use small diaphragms. In observations according to the TEP network we used 23-arcsec diaphragms, and this could be possible only because of the large declination of CM Dra (57°). For small declinations approaching zero, satisfactory manual guiding turned out practically impossible even by using such relatively large diaphragms. At last, in 2000 we managed to replace a human eye by a CCD guiding system. This allowed us to use diaphragms up to 16-arcsec for any declinations and seeing conditions and to obtain continuous light curves up to 12 h in length fully automatically. The photometer was also modernised. We added the channel for continuous measurements of the sky background. Now we sometimes perform observations of CM Dra with the goal to measure precise eclipse minima times (see Deeg et al. 2008). The precision of these automatic observations turns out 0.003–0.004 mag (a time resolution of 128 s).

3 Observations of intermediate polars

Intermediate polars form a subclass of cataclysmic variables in which a magnetic white dwarf accretes material from a late-type companion filling its Roche lobe. The rotation of the white dwarf is not phase-locked to the binary period of the system. Because the magnetic axis is offset from the spin axis of the white dwarf, this causes oscillations in the X-ray and optical wavelength bands. The X-ray oscillation period is usually identified as the spin period of the white dwarf. In addition to the spin and orbital periods, the reprocessing of X-rays in some part of the system that rotates with the orbital period gives rise to emission that varies with the beat period. This beat period is often called orbital sideband.

The intermediate polar V709 Cas was discovered as the X-ray source, which showed an X-ray period of 312.8 s (Haberl and Motch 1995). However, the CCD photometric observations made by Motch et al. (1996) did not reveal optical oscillations at the X-ray period. In 1999 we performed observations of V709 Cas with a total duration of 46 h within 6 consecutive nights and for the first time detected the optical oscillation with a period of 312.77 ± 0.04 s, which corresponds to the X-ray period. In addition, we detected the orbital sideband with a period of 317.94 ± 0.04 s and its first harmonic (Kozhevnikov 2001). Although the duration of the observations made by Motch et al. (27 h) was less than the duration of our observations, this seems not the only reason of their unsuccessful observations, which were not able to detect any optical short-period oscillations in V709 Cas. As seen in Fig. 3 in Kozhevnikov (2001), the first harmonic of the orbital sideband, which has a 159-s period, shows the peak in the power spectrum, which is more prominent among the surrounding noise peaks, and, therefore, this oscillation is easier to detect. But the CCD system used by Motch et al. had insufficient time resolution to detect this short-period signal whereas the time resolution of our photometer is practically unlimited.

Although the cataclysmic variable EI UMa has been known for a quarter of a century, until recently its nature remained unclear. Recent X-ray observations of EI UMa revealed that its hard X-ray spectrum is typical of intermediate polars (Baskill et al. 2005). In addition, Baskill et al. found an X-ray candidate period of 742 ± 5 s. However, optical photometry performed by Reimer et al. (2008) revealed no continuous coherent oscillation. The peaks in the power spectra with periods close to the X-ray

period appeared only episodically. Reimer et al. suggested to attribute EI UMa to stars, in which coherent oscillations are not detectable due to an insufficient deviation of the magnetic axis from the spin axis, and to call such objects "hidden" intermediate polars. In March–April of 2008 we performed photometry of EI UMa with a total duration of 60 h within 13 nights. We detected an oscillation with a period of 769.63 ± 0.10 s, which was completely coherent during one month of observations (Kozhevnikov 2010). Although the oscillation cannot be directly detectable in each individual night due to its small amplitude, the power spectrum of the data incorporated into the common time series demonstrates that this oscillation is present in all the data and is continuous. This follows from the close resemblance of the power spectrum in the vicinity of the oscillation peak and the window function (see Fig. 4 in Kozhevnikov 2010). Although the total duration of the observations made by Reimer et al. was quite large, these data were scattered over 2 years. This excluded the possibility to analyse the data incorporated into common time series because of randomly distributed large gaps complicating the window function and due to small amplitude of the oscillation. This is the plausible reason of the incorrect conclusion that EI UMa is a "hidden" intermediate polar.

The intermediate polar nature of V515 And was discovered by Bikmaev et al. (2006). They detected an optical oscillation with a period of about 480 s. Butters et al. (2008) detected an X-ray period of 465.68 ± 0.07 s and by that confirmed this discovery. However, the oscillation period found in X-rays by Bonnet-Bidaud et al. (2009) turned out to be somewhat different, namely 469.75 ± 0.27 s. All these periods were of rather low precision due to insufficient length of the observations. In 2008 we performed photometric observations of V515 And. From these observations we learned that the oscillations in V515 And have large amplitudes, and, therefore, the spin period of the white dwarf can be measured with high precision allowing us to search for spin-up or spin-down. To obtain the oscillation periods with high precision, in 2009 we performed additional observations. All our observations span a total duration of 233 h within 33 nights. We found two oscillations with periods $465.484\,93 \pm 0.000\,07$ and $488.618\,22 \pm 0.000\,09$ s (Kozhevnikov 2012). The high precision of the oscillation periods, which was achieved due to the large observation coverage and the low noise level in the power spectra, allowed us to obtain oscillation ephemerides with a formal shelf life of about 100 years. This high precision in itself is a valuable new result sufficient to merit a publication in a journal of world standing like MNRAS.

4 Observations of superhumps

Many cataclysmic variables of short orbital period have light curves with prominent humps, which reveal periods slightly longer than the orbital period. These are called "superhumps" because they are characteristic of the SU UMa-type dwarf novae in superoutburst. Some cataclysmic variables show superhumps in their light curves during the normal brightness state. These superhumps are called permanent superhumps. Permanent superhumps can either be a few per cent longer than the orbital periods and they are called "positive superhumps", or they can be a few per cent shorter – "negative superhumps". Typical full amplitudes of permanent superhumps are about 5–15%, but they are highly variable and sometimes even disappear from

the light curve. The periods of the superhumps are unstable and usually show appreciable wobbling. The positive superhump is explained as the beat between the binary motion and the precession of an eccentric accretion disc in the apsidal plane. The negative superhump is explained as the beat between the orbital period and the nodal precession of the disc tilted to the orbital plane.

Spectroscopic observations of the dwarf nova AT Cnc by Nogami et al. (1999) revealed the orbital period equal to 4.826 ± 0.014 h. In addition, their photometry revealed an oscillation with period candidates of 0.132, 0.124, 0.142 and 0.249 d. These period candidates turned out too short or too long in comparison with the orbital period. Hence, the observed oscillation might not be superhumps. Therefore, Nogami et al. suggested that the oscillation may be caused by asynchronous rotation of a magnetic white dwarf. In February–March of 2003 we performed photometry of AT Cnc within 13 nights. Two sets of our data revealed variations with periods of 4.65 ± 0.02 and 4.74 ± 0.02 h (Kozhevnikov 2004). This signal varied in period and in phase on a time-scale of weeks, as is typical of superhumps. A comparison with the orbital period shows that this signal is a negative superhump because the average period of brightness variations is a bit shorter than the orbital period. The length of 11 of our individual light curves was larger than the orbital period, and the length of 4 of them was larger than the doubled orbital period, whereas the total duration of the photometric observations obtained by Nogami et al. within three nights was only 13.2 h, i.e., the average length of their individual light curves was less than the orbital period. Obviously, analysis of such short light curves revealed only the noise caused by phase instability and other non-periodic brightness changes, which are typical of cataclysmic variables.

KR Aur is a cataclysmic variable of the VY Scl-subtype. Such stars can occasionally come into extended low states. Spectroscopic observations by Shafter (1983) revealed that KR Aur has an orbital period of 3.907 h. Singh et al. (1993) detected large-amplitude quasi-periodic oscillations in this star, with periods in the range of 500–800 s. There were also indications of a modulation with a period of about 4 h. This modulation might represent the orbital period or might be a type of superhump. However, Kato et al. (2002) conducted photometric observations of KR Aur and found no modulation with such a period. We decided to clarify whether a photometric signal near the orbital period is present in KR Aur, and the first observational night clearly showed such a modulation. Careful analysis of all our observations spanning a total duration of 107 h within 13 nights in January–February of 2004 revealed a period of 3.771 ± 0.005 h (Kozhevnikov 2007). This is 3.5% shorter than the orbital period. Obviously, the observed oscillation is a negative superhump. Most our individual light curves were larger than the doubled orbital period, whereas only 3 of 18 individual light curves by Kato et al. slightly exceeded the orbital period. This is the plausible reason that superhumps were not detected by them.

At first V378 Peg was classified as a B-type subdwarf (Wesemael et al. 1992). Koen and Orosz (1997) conducted photometric observations of V378 Peg and found flickering, which is a hallmark of cataclysmic variables. In addition, they obtained the spectrum, which revealed emission lines also typical of cataclysmic variables. Although V378 Peg is a rather bright star, for a long time this star underwent no detailed study. Even the orbital period until recently has not been determined. In September–November of 2011 we performed observations of V378 Peg, spanning a

total duration of 75 h within 14 nights. Analysis of the data allowed us to detect the oscillation with a period of 3.238 ± 0.003 h (Kozhevnikov 2012). Careful analysis of the data showed that this oscillation is unstable both in amplitude and in phase with random phase changes within 10–20% of the period. Because of its instability, we attributed this oscillation to superhumps. It is worth to note that half of our individual light curves were larger than the doubled period. Shortly after publishing our results, the superhumps in V378 Peg with the period of 3.23 ± 0.01 h were confirmed by Ringwald et al. (2012). In addition, they found the spectroscopic orbital period equal to 3.326 h. Thus, the detected superhumps are negative superhumps. It is interesting that, although negative superhumps are rare, it is the third successive case when we detected negative superhumps.

5 Current observations

The intermediate polar 1RXS J063631.9+353537 (hereafter J06363) was observed only once (Gänsicke et al. 2005) and, therefore, its discovery must be confirmed. Moreover, the spin period of the white dwarf was measured with a low precision. This precision makes it impossible to obtain a long-term oscillation ephemerid. From our observations we learned that the short-period oscillation in J06363 has large amplitude and, therefore, the oscillation period can be measured with high precision. Despite the relatively low brightness of the star (16 mag), this oscillation is visible directly in individual light curves. One of our light curves of J06363 is presented in Fig. 1. During 2012 we performed observations of J06363 with a total duration of 133 h and found the oscillation period equal to 1008.3103 ± 0.0061 s. Its precision is still insufficient to obtain a long-term oscillation ephemerid. Therefore, in 2013 we continued observations. The case of observations of J06363 is quite instructive. This star is faint and completely invisible by eye. We managed to centre this star in the diaphragm due to the precise telescope movements controlled by the computer.

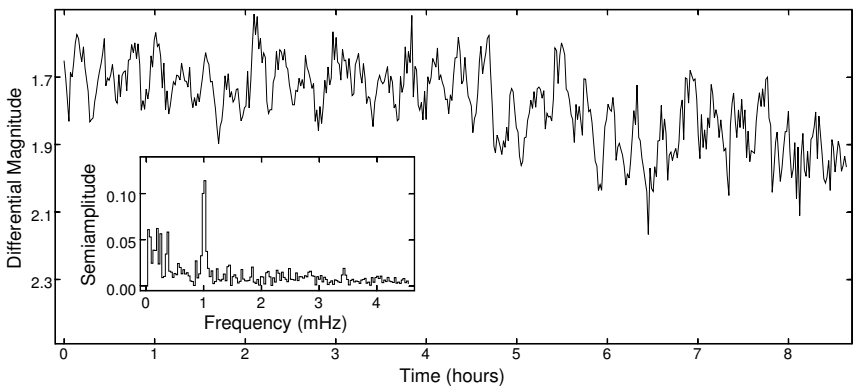


Figure 1 Differential light curve of the intermediate polar 1RXS J063631.9+353537 obtained 14 February 2012 and its amplitude spectrum.

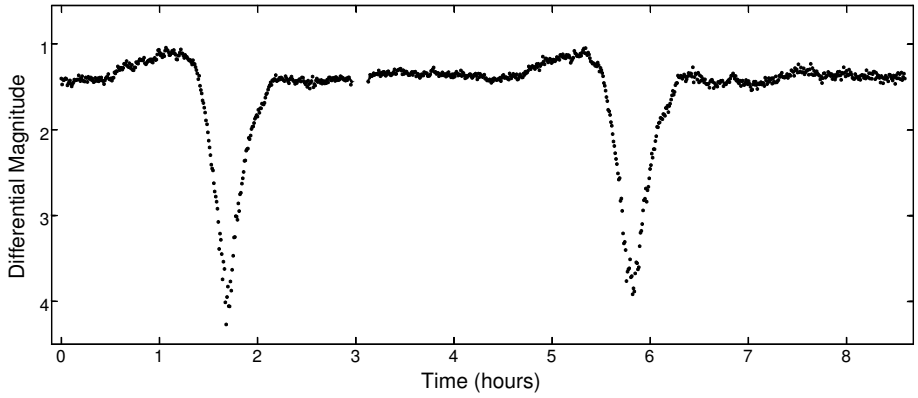


Figure 2 Light curve of the eclipsing cataclysmic variable HBHA 4705-03 obtained 10 December 2012. At minimum brightness the star fades up to 18 mag.

The cataclysmic variable HBHA 4705-03 showed eclipses (Yakin et al. 2013). There were also indications that this star is an intermediate polar (Ritter and Kolb 2003). In 2012 we performed photometry of this star with a total duration of 80 h. These observations, however, seem insufficiently prolonged to confirm the intermediate polar nature of HBHA 4705-03. Therefore, in 2013 we will continue observations of HBHA 4705-03. One of our light curves of HBHA 4705-03 is presented in Fig. 2. This light curve is also instructive. At maximum brightness the star has a magnitude of about 15 mag. As follows from the light curve, at minimum brightness the star fades up to 18 mag. We used 16-arcsec diaphragms. Therefore, at minimum brightness the counts of the star were only a few percents of the counts of the sky background. The possibility to observe such faint stars by using a photoelectric photometer in the atmospheric conditions of Kourovka observatory seems amazing. Obviously, this possibility emerges due to the usage of the sky background channel.

Conclusion

From our experience of photometric observations of cataclysmic variables we can make the following conclusions:

1. A large amount of observations allow us to obtain valuable new results even for well investigated objects.
2. This large amount of observations must be reasonably restricted according to a formulated task.
3. Observations of intermediate polars during two years or more are sensible when their short-period oscillations have large amplitudes because the precision of the oscillation period depends on both the noise in the power spectrum and the observational coverage. Anyway, very high precision of the oscillation period cannot be achieved when the oscillation is barely detectable.
4. When the oscillation in an intermediate polar is not easily detectable due to its low amplitude, the observations (50–100 h) must be concentrated within a

short time of about 1 month. If observations are scattered over 2 years, the oscillation can be lost in the complicated structure of the window function.
5. Permanent superhumps can be safely detected if the length of the individual light curves is larger than the doubled superhump period. When their length is less than the superhump period, the superhump turns out nearly completely removed due to low-frequency detrending, which is a standard procedure in time series analysis.
6. It seems less sensible to observe a permanent superhump within a time interval of larger than 3 months because of instability of the superhump period. Anyway, large observation coverage will give no high precision of the superhump period due to its instability.
7. The precise movements of the 70-cm telescope controlled by the computer make it possible to centre stars invisible by eye in the photometer diaphragms.
8. Usage of the sky background channel makes it possible to observe photoelectrically very faint stars, which only slightly exceed the sky background.

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