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Several Methods of Estimating Times of Minima in Cataclysmic Variables And Some Fesults for EX Dra

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Abstract. For eclipsing cataclysmic stars are used several methods of estimating the times of the minima. Eclipses provide a fiducial mark in time and if the minima times are accurate, we can determine the orbital period with a high precision. For dwarf novae in quiescence with short exposure times is appropriate the Wood's derivative method, with longer exposure times is better to use the spline fitting method and it is better to omit estimated times for dwarf novae in outburst to ensure more precise timings. The determined times of the minima by spline fitting derivative method and the constructed observed-minus-calculated diagram depict a 21 year modulation of the orbital period of EX Dra.

Introduction

Cataclysmic variables (CVs) are semi-detached binaries, where the late-type star overfills its Roche lobe and matter is transferring from Lagrangian point L1 toward to the white dwarf (WD). Coriolis force causes that the stream of the matter is not falling straightforward to the white dwarf. An accretion disc is formed around the WD with weak magnetic field. Once the disc was established, the transferring matter hits accretion disc and create a shock-heating area called bright spot. A strongly magnetic WD can destroy a formation of the accretion disc and the matter is transferring along the magnetic field lines onto WD. Reader can learn more about CVs in good review-books by *Warner* [1995] and *Hellier* [2001]. The binary seems to be eclipsing when the observer is near the orbital plane of the binary or inclination $90° \geq i \gtrsim 70°$,

Accretion disc state depends on a mass-transfer rate. At a low transfer rate (but still higher as accretion via an accretion disc onto WD) the accretion disc will fill up, increasing its surface density. More denser disc raises its temperature due to the greater viscous heating, until ionisation temperature of hydrogen is reached. Opacity is extremely sensitive to the temperature in partially-ionized gas. Any further increase of mass in the disc produces sharply grow of the temperature. When the gas is full-ionised, opacity loses its sensitivity and the disc is in a new equilibrium state with high viscosity, which is caused by Balbus-Hawley instability [e.g., *Hawley and Balbus*, 1998] thanks to many charged particles in the ionised disc. Increased viscosity increases the flow of material inwards. Surface density in the disc is reducing because mass-transfer slower replenishes matter to the disc, temperature drops until hydrogen becomes again partially-ionised. Then ions recombine, temperature and viscosity drop and the disc returns to the state as in the beginning.

At a high transfer rate is the disc still in hot, ionised and high-viscosity state due to high viscous heating. Changing state of the accretion disc is typical for *dwarf novae* and permanent high state in the accretion disc is typical for *nova-like variables*.

Dwarf novae

Subgroup of CVs with recurring outbursts in the accretion disc is called dwarf novae. Accretion disc switches from cold, un-ionised, low-viscosity state called *quiescence* to hot, ionised, high-viscosity state called *outburst* as is described in last section. Outburst recur every 10–500 days with amplitude 1–5 mag.

Z Cam type shows periods of constant brightness called standstills with brightness ≈ 0.7 mag lower as in the maximum of the outburst when the accretion disc is still in high-state.

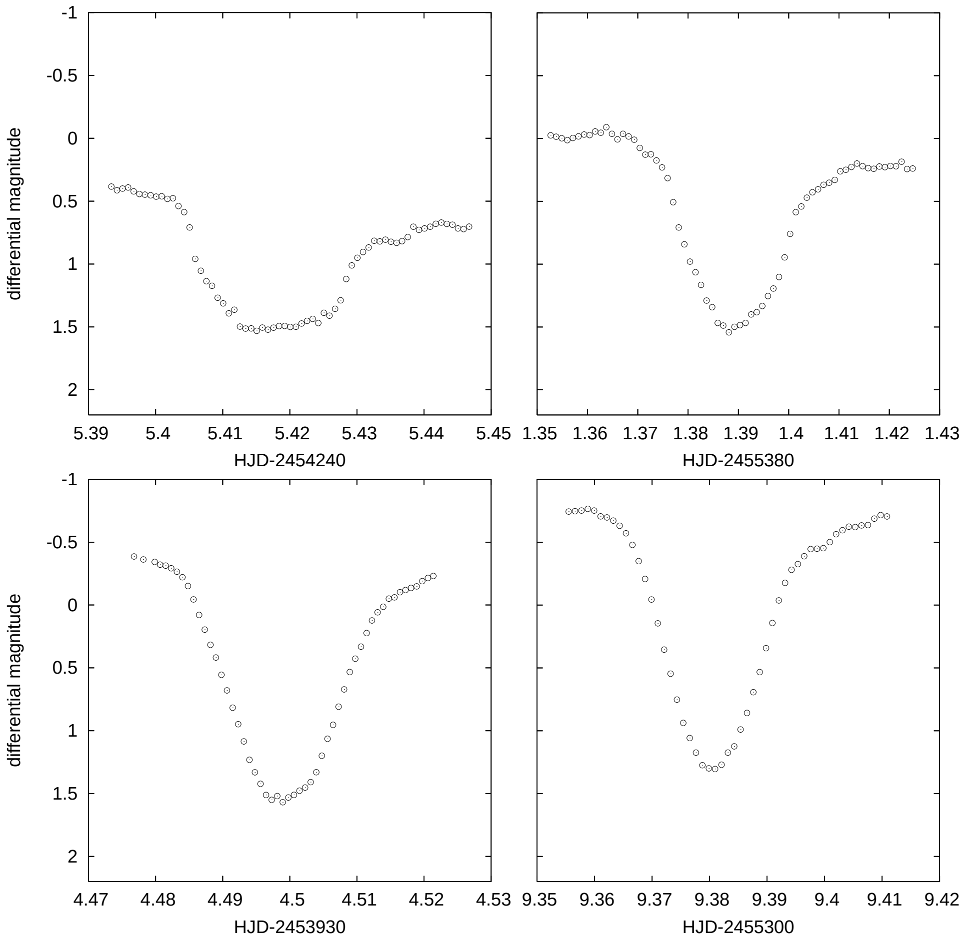

Figure 1. Asymmetry of eclipse curve of the dwarf nova EX Draconis in R band during rise of the outburst. *Top left*: quiescence. *Top right*: early rise. *Bottom left*: late rise. *Bottom right*: maximum of the outburst. Shape and depth of the eclipse light curve is changed during outburst. Maximum uncertainty of each measurement is 0.02 mag.

Z Cam stars are boarder line between dwarf novae and nova-likes. Standstill is always initiated by outburst, then Z Cam star acts as nova-like for a while, until something happens (perhaps star spot passing across a Lagrangian point L1), which causes the mass-transfer to drop again.

Dwarf novae with mass-ratio $q \lesssim 0.3$ have huge Roche lobe of WD and the disc radius can achieve the 3:1 resonance with secondary star and the disc becomes elliptical. In the light curve can be seen superoutburst lasting more days that normal outburst and slightly brighter. Superoutbursts occur after several succession of normal outbursts depending on the mass-transfer rate, during superoutburst is visible hump-shape modulation called superhump with period a few percent longer as the period of the orbital cycle. This dwarf novae are referred as *SU UMa type*.

U Gem type stars are called dwarf novae with normal outbursts. Recurrence of outbursts is semi-regular, each U Gem star has its own typical average period depending on the mass-transfer rate.

Estimating times of the minima in eclipsing binaries can be used to determine precise value of orbital period. In Figure 1 we can see the asymmetrical shapes of the eclipse light curves of the dwarf nova EX Dra during the progress of an outburst. The shape of the light curve changes throughout a outburst from very asymmetrical U-shaped to deep more symmetrical V-shaped but decreasing and increasing branch have still different steepness. Methods of estimating minima times for detached binaries (e.g. Kwee van Woerden method [*Kwee and van Woerden*, 1956]) are not usable for asymmetrical light curves of the dwarf novae.

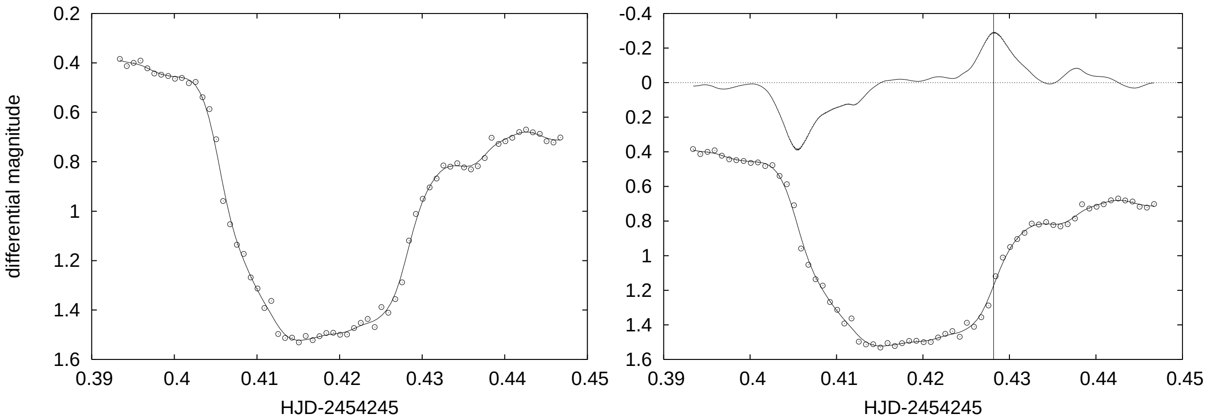

Figure 2. The spline fitting derivative method for dwarf nova EX Dra. 1^{st} step is depicted on the left and 2^{nd} and 3^{rd} step on the right. The time of the mid-egress of the WD is local maximum of the derivative curve. Maximum uncertainty of each measurement is 0.02 mag.

Better than to estimate time of the mid-eclipse is to estimate times of egress or ingress of three eclipsed bodies—white dwarf, accretion disc or bright spot. Radius of the accretion disc increases during an outburst, accordingly times of the ingress and egress of the disc are unstable and therefore unsuitable. Bright spot is on the edge of the disc, increases with the disc and for estimating minima times is unsuitable too. The only possible time points are ingress and egress of the WD, but ingress of the bright spot occur near ingress of the WD, so the light changes of ingress of the WD are contaminated by light changes of the bright spot. During outburst is the WD outshone by the disc and light changes of the WD are poorly visible. Therefore the best possibility is to estimate the egress of the WD during quiescence. If we estimated both egress and ingress time, we can estimate time of eclipse of the WD center as average time from this two times.

First method of estimating egress of the WD is the spline fitting derivative method [e.g., *Fiedler et al.*, 1997]. This method is depicted in Figure 2 and individual steps are:

1. Points of light curve are smoothed by an approximative cubic spline function.
2. Derivation of the approximative cubic spline function.
3. The time of the mid-egress is time of maximum of the derivative.

Second method was proposed by *Wood et al.* [1985]. Method uses median and average filter for smoothing of the points of the light curve. Median filter of a given width changes each point of the light curve to a median of a surrounding points of the given width and average filter changes each point on a average value of the points in a surrounding of the given width. This method is depicted in Figure 3 and individual steps are:

1. Points of light curve are smoothed by median filter. This step can be omitted, if the measurements have small uncertainties.
2. Derivative of smoothed light curve.
3. Using average filter of width equal to the expected duration of egress.
4. A spline function is fitted to points that are not lying within expected egress.
5. Times of the beginning and the end of the egress of the WD are the same as times where the derivative differs greatly from the spline function.
6. The time of the mid-egress of the WD is average value of these two values.

Novae and Nova-like variables

Eruption of the *classical novae* have typical amplitude of 8–15 mag and it is not seen to repeat. The cause of a nova eruption is nuclear chain-reaction on the surface of a white dwarf.

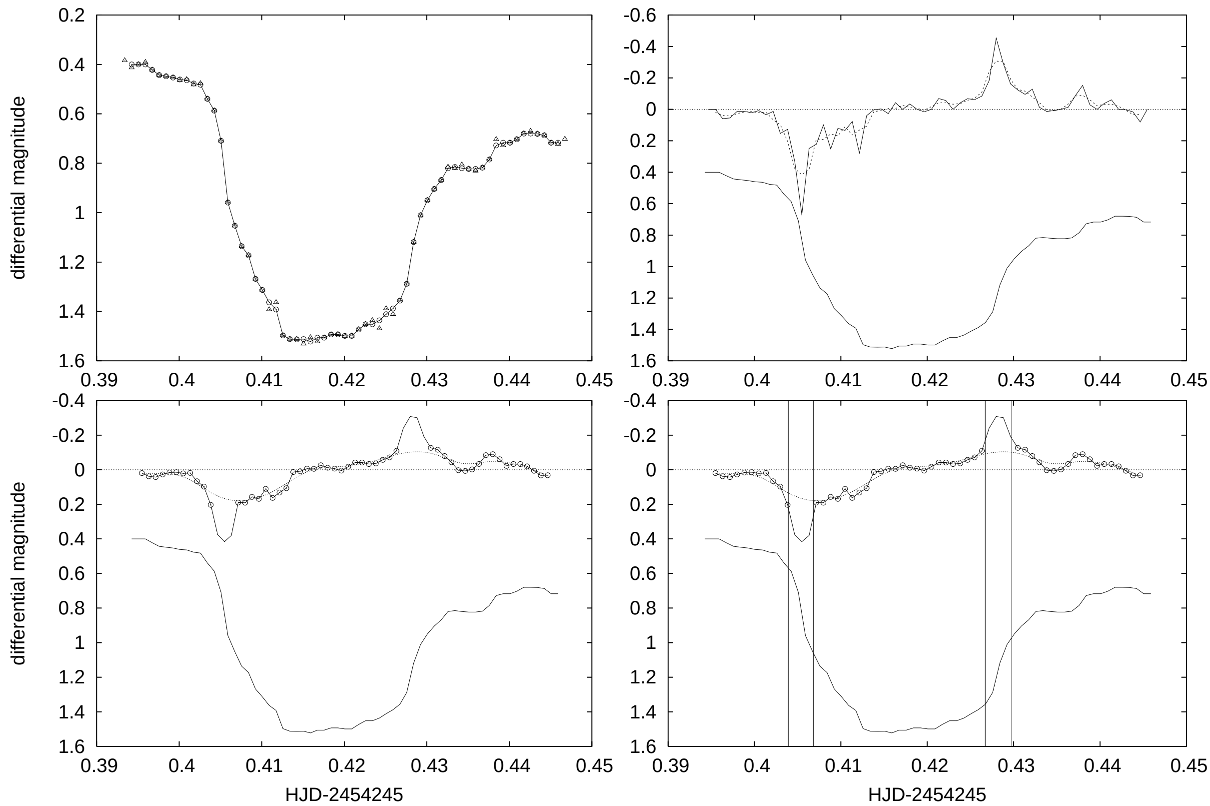

Figure 3. The Wood's derivative method [*Wood et al.*, 1985] for dwarf nova EX Dra. 1^{st} step is on the top left, 2^{nd} and 3^{rd} step is on the top right, 4^{th} step is on the bottom left and 5^{th} step is on the bottom right. The time on the mid-egress of the WD is an average value of the beginning and the end of the egress. Maximum uncertainty of each measurement is 0.02 mag.

If a binary is seen to undergo more than one nova eruption it belongs to sub-class *reccurent novae*.

Nova-like variables have accretion disc still in hot, ionised and high-viscosity state similar to the outburst in dwarf novae. *UX UMa type* stars have still constant brightness except of the eclipses. *VY Scl type* stars spending much of their time in high-state, but sometimes they switch into low-state like quiescence in the dwarf novae during which mass-transfer drops or shuts off completely.

The accretion disc outshines the WD and the bright spot. The egress of the WD can be hardly identified and therefore derivative methods are not usable. Precise time of the mid-eclipse is hard to estimate because of asymmetrical shape of the eclipse. Many authors use a parabola fitting method [e.g. *Thoroughgood et al.,* 2004] to the eclipse light curve or to the lower half of the eclipse curve. It is important to use same method for all estimations of the mid-eclipse times of each nova or nova-like variable to ensure smaller systematic errors. The parabola fitting method is depicted on the left part of Figure 4 and individual steps are:

1. Fitting parabola to the eclipse part of the light curve (or to the lower half of the eclipse part of the light curve).
2. The time of the mid-eclipse is minimum of the parabola.

Magnetic CVs

Strong magnetic field of the WD can disrupt the accretion disc, either totally in *polars* or partially in *intermediate polars*. The most of the luminosity is radiated by hot spot (area on the WD's surface where the stream of matter is falling onto WD). In this type of the CVs can be

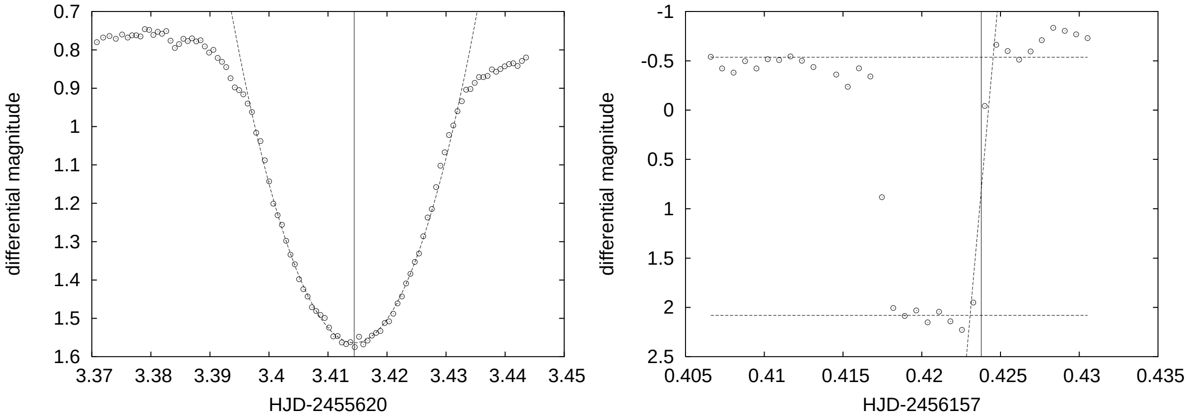

Figure 4. *Left*: The parabola fitting method for nova-like variable AC Cnc. *Right*: The straight lines fitting method for magnetic cataclysmic variable star HU Aqr. Maximum uncertainty of each measurement is 0.02 mag.

visible variations of the mass transfer directly by brightness variations in the light curve. The WD and hot spot are hidden by the secondary star at same time and then the stream of matter. The best time point to estimate is mid-egress of the hot spot. If we estimate both egress and ingress time, we can estimate time of a eclipse of the hot spot center as same as in the dwarf novae. The straight line fitting method [e.g. *O'Donoghue et al.,* 2003] is depicted on magnetic CV star HU Aqr on the right part of Figure 4 and individual steps are:

1. Fitting straight line to the out-of-eclipse points of the light curve.
2. Fitting straight line to the total part of the eclipse light curve.
3. Fitting straight line to the egress part of the eclipse light curve.
4. The time of the mid-egress is taken to be the time when the third line crosses the average level of the first two lines.

EX Draconis

EX Draconis ($\alpha_{2000} = 18^h04^m15.1^s$, $\delta_{2000} = 67°54'07''$) is a dwarf nova above period gap with orbital period $P_{\rm orb} = 0.2099373$ d and brightness $m_{\rm V} = 13$–17 mag. EX Dra was observed from 2004 to 2011 at Ondřejov Observatory and at Kolonica Saddle Observatory. Details about telescopes, cameras and times of the measurements are in [*Pilarčík et al.*, 2012].

New times of the minima were estimated by the spline fitting derivative method. From the timings estimated from these observatories and from the timings collected from the literature [*Fiedler et al.*, 1997; *Baptista et al.*, 2000; *Shafter and Holland*, 2003] was calculated ephemeris [*Pilarčík et al.*, 2012]

$$Min. = BJD\,2452474.80513(10) + 0.209937316(13) \cdot E + 0.00184(9) \cdot \sin 2\pi \left(\frac{E - 3520(360)}{36600(2300)} \right).$$

The orbital period is changing with the modulation period $P_{\rm mod} = 21.1 \pm 1.3$ yr and the amplitude $A = 159 \pm 8$ s.

Discussion

The best method for the estimating minima times for the dwarf novae in quiescence is the Wood's derivative method, but its inaccuracy increases with the exposure times of the measurements. The spline fitting method is more precise for measurements with longer exposure times. If dwarf nova is in outburst, it is better to use parabola fitting method as same as for

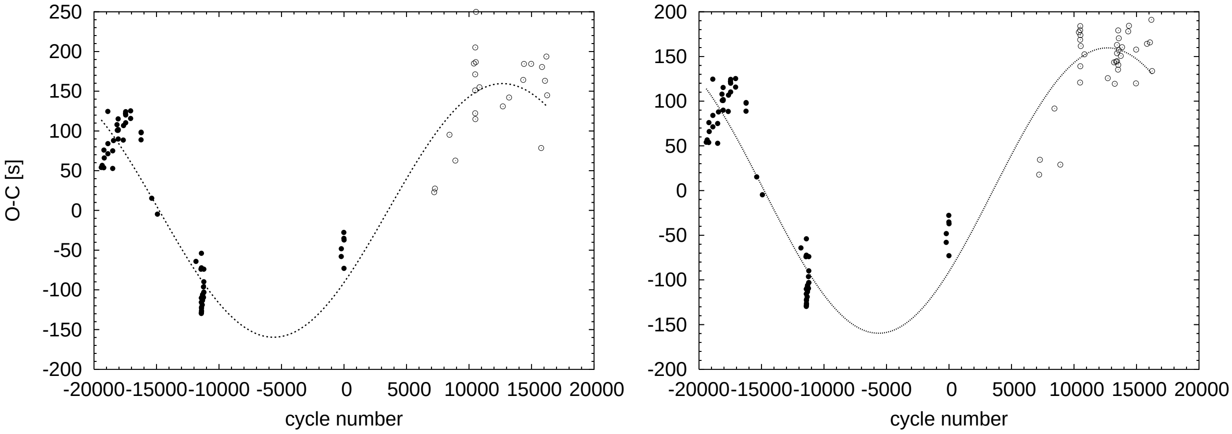

Figure 5. *Left*: O-C diagram with minima estimated by the spline fitting derivative method. *Right*: O-C diagram with minima estimated by the Wood's derivative method. Times of minima obtained from literature is depicted by full circles and from measurements from Ondřejov and Kolonica Saddle by open circles.

nova-like variables, because the accretion disc is also in high state and eclipse light curve is very similar.

By parabola fitting method is estimated time of the eclipse of the accretion disc center, by derivative method is estimated egress or ingress of the WD and from this two times is estimated center of the WD eclipse. The center of the distribution of accretion disc brightness do not have to correspond with the WD center, so this two estimated times in other states of the accretion disc are not the same times. Therefore it is better to omit estimated times for dwarf novae in outburst by parabola fitting method to ensure more precise timings. Usually dwarf novae are more often in quiescence as in outburst, therefore it is omitted only a few minima times.

In Figure 5 are O-C diagrams for dwarf nova EX Draconis estimated both by spline fitting derivative method and by Wood's derivative method. It is visible that minima from Ondřejov and Kolonica Saddle measurements have bigger dispersion estimated by Wood's method as by spline fitting derivative method. Therefore, for the observation of EX Draconis obtained at Ondřejov Observatory and at Kolonica Saddle Observatory with 30 s and 60 s exposure times is better to use the spline fitting method for estimation of the minima times. For each cataclysmic variable is important to use the same method for all estimations of the minima times to ensure precise timings.

Conclusion

For dwarf novae in quiescence with short exposure times is appropriate the Wood's derivative method and with longer exposure times is better the spline fitting method. For nova-like variables is suitable the parabola fitting method and for magnetic CVs the straight lines fitting method. All methods are depicted in individual Figures 2, 3, 4.

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