Investigating AM Her Cataclysmic Variables with the Optical Pulsar Timing Analyzer — OPTIMA

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Abstract. We focus on short–period eclipsing binaries that belong to a class of Cataclysmic Variables (CVs). They are known as polars and intermediate polars, closely resembling their prototype AM Herculis. These binaries consist of a red dwarf and a strongly magnetic white dwarf, having orbital periods of only a few hours. Monitoring eclipses of these typically faint sources demands high-time resolution photometry. We describe the very recent results obtained for two CVs, HU Aqr and DQ Her, which were observed with the Optical Pulsar Timing Analyzer (OPTIMA). The new observations of HU Aqr confirm that the O–C (Observed minus Calculated) diagrams exhibit variations known for this binary which can be explained by a single, massive Jupiter–like planet, possibly accompanied by a very distant companion.

OPTIMA is a fast, single-photon sensitive optical photometer and polarimeter (Straubmeier 2001; Kanbach et al. 2003, 2008; Stefanescu 2011). It uses optical fibres to gather light from fixed apertures in the focal plane in to SPAD (Single-Photon Avalanche Diode) detector modules, while the field surrounding the apertures is imaged using a standard CCD camera. The photometer part of the instrument contains eight fibre–fed single photon counters — SPADs, and a GPS for the time control. There are seven fibres in bundle and one separate fibre located at a distance of 1 arcmin. Single photons are recorded simultaneously and separately in all channels with absolute UTC time–scale tagging accuracy of ~ 5 ns. The quantum efficiency of the SPADs reaches a maximum of 60% at 750 nm and lies above 20% in the 450–950 nm range.

The system was designed from scratch as a guest instrument, easily adapted to different telescopes. It can be reconfigured for photometric, polarimetric or spectroscopic use within one observing run. OPTIMA was successfully used at various observatories. As its name implied, OPTIMA was initially designed for optical pulsar studies, however it is not limited to this subject only. There were many successful measurements acquired with OPTIMA that are not pulsar related. Some of them are presented here.

http://www.mpe.mpg.de/OPTIMA
Figure 1. Example light curves of DQ Her and HU Aqr obtained during 2011 and 2012 observing campaigns at Skinakas Observatory using the OPTIMA photometer working with 1.3-m telescope (the left and the right panel, respectively). Data binning is 1 second.

**DQ Her Observations by OPTIMA**

DQ Herculis (or Nova Herculis 1934) was a slow, bright nova occurring in December 1934, reaching a peak magnitude of 1.5 (Adams et al. 1935). It is classified as an Intermediate Polar. The binary consists of a red dwarf star (M2 type) and a fast rotating, highly magnetic white dwarf (DBe type). The rotation period $P \sim 72$ seconds is easily resolved in our new OPTIMA observations. The orbital period of DQ Her ($P_{\text{bin}} \sim 4h \ 39m$) lies above the period gap (> 3 hours). DQ Her resembles closely the AM Her type stars in many ways, although the latter are spin–orbit synchronised, and generally have shorter orbital periods which prevents the formation of an accretion disk.

In 2009, Dai and Qian analysed the available observations of DQ Her, spanning almost 50 years. They reported the presence of a third object in the system to explain the orbital period variations observed in the (O–C) diagram. If the putative third body is confirmed, it would likely turn out to be a brown dwarf.

However, the DQ Her light curves collected over such a long period of time likely suffer of observational biases and errors. During the 2011 and 2012 seasons, we gathered new, optical high-time resolution photometric data with OPTIMA. An example light curve of DQ Her is shown in the left panel of Fig. 1. We expect that such observations will be helpful to reveal the true origin of the large magnitude (O–C) variations and confirm or withdraw the planetary hypothesis. This project requires a long–term monitoring of the object.

**HU Aqr — A Single Jovian Companion?**

The eclipsing polar HU Aquarii (HU Aqr) consists of a strongly magnetic WD accompanied by a red dwarf (spectral type M4V). The orbital period is about 125 minutes. This is one of the brightest polars at X-ray energies and in the optical domain with visual magnitudes ranging from 14.6 to 18. Therefore, it has also been one of the most intensively studied systems so far.

For the sky background monitoring, we usually choose hexagonally located fibres that are not by chance pointed to any source, hence recording the background only, and those with the response most similar to that of the central fibre, when the instrument is targeted at the dark sky. An example of the background subtracted light curve, obtained in July 2012, is shown in the right panel of Fig. 1.
Since the discovery in 1991, HU Aqr eclipses are constantly and carefully monitored. The polar exhibits relatively large (O–C) variations unjustified by the astrophysics of the binary. Qian et al. (2011) explained this by the presence of two jovian companions, but the proposed 4-body planetary system was proved strongly unstable (Wittenmyer et al. 2012). In our recent paper (Goździewski et al. 2012), we performed a detailed study of all available data in the literature, in terms of a new Light Travel Time (LTT) ephemeris model \( T_{ep}(l) \), and carried out new OPTIMA observations. This model is formulated w.r.t. the Jacobi coordinates with the origin in the mass center of the binary, i.e., \( (O–C) = T_{ep}(l) - t_0 - lP_{\text{bin}} - \beta l^2 - \sum_p \zeta_p \), for a given epoch \( t_0 \), cycle number \( l \), binary period \( P_{\text{bin}} \) and period damping factor \( \beta \) (i.e., the quadratic ephemeris).

Contribution \( \zeta_p(t) \) of a putative planet (\( p = 1, 2, \ldots \)) to the (O–C) deviation is:

\[
\zeta_p(t) = K_p \left[ \sin \omega_p \left( \cos E_p(t) - e_p \right) + \cos \omega_p \sqrt{1 - e_p^2} \sin E_p(t) \right],
\]

where \( K_p, e_p, \omega_p \) are the semi-amplitude of the LTT signal, eccentricity, argument of the pericenter, respectively. The orbital period \( P_p \) of a companion, and its time of pericenter passage are introduced indirectly through the eccentric anomaly \( E_p(t) \).

We found that the (O–C) variations of HU Aqr are best explained by a quasi-periodic signal appearing in terms of the quadratic ephemeris, which can be interpreted through the presence of \( \sim 7 \) Jupiter masses planet, in a \( \sim 10 \) yr quasi-circular orbit (Goździewski et al. 2012). In fact, this result is achieved thanks to superior timing accuracy of OPTIMA in the optical domain. The first OPTIMA observations of HU Aqr were performed in 1999. Since then, further 64 eclipses spanning more than 55,000 orbital cycles have been recorded. Looking at these observations only, we detected a clear,
quasi-sinusoidal variation of the (O–C). All available mid-egress moments derived from different instruments and spectral domains exhibit much more complex and apparently multi-modal pattern of the (O–C). It is usually explained in the literature by the superposition of Keplerian orbits. Most likely false detection of the second planet (signal) proposed by Qian et al. (2011) can be related to mixing observation in different spectral windows and instrumental errors. This is confirmed by the best-fit solution to the OPTIMA observations only (Fig. 2), including the very recent data (an example light curve is shown in the right panel of Fig. 1). It nicely follows our single-planet (quasi-sinusoidal signal) model with the quadratic ephemeris in Goździewski et al. (2012). The origin of relatively large quadratic term is yet uncertain. It might appear due to very distant companion. To confirm or withdraw the planetary hypothesis, or the (O–C) signal coherence, a long-term monitoring of the HU Aqr is necessary.

Conclusions

OPTIMA is an unique instrument, particularly useful to observe short-period eclipsing CVs binaries. Thanks to its specific design, it provides ultra-high time resolution photometry and polarimetry, required for characterising these intriguing objects, and resolving their complex astrophysics. Recently, these targets become particularly interesting due to a number of announcements of their planetary companions. OPTIMA observations are crucial to verify a doubtful discovery of a 2-planet system around HU Aqr (Goździewski et al. 2012). It might also help to study the LTT effect, which is presumably present in the case of DQ Her and other CVs.

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