High time resolution observations of Cataclysmic Variables with OPTIMA

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Abstract. The high-speed photometer ’OPTIMA’, short for Optical Pulsar Timing Analyzer, was used to record optical (450-950nm) light curves of selected cataclysmic variables of type AM Her (Polars) with sub-second temporal resolution. The objects RX J0704+62, RX J0953+14, and EK UMa were re-observed several years after their discovery to provide up to date light curves with good statistics. The eclipsing binary DP Leo, which had been observed during 20 years previous to the OPTIMA measurements, was shown to have an orbital ephemeris with a quadratic term. For HU Aqr we have collected data over the years 1999 to 2007. HU Aqr evolved in luminosity from a high state in 2000 to a low state that persists since 2001. We detected variability in HU Aqr in the form of optical flashes with timescales of seconds.

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INTRODUCTION

Cataclysmic variable binary stars classified after the example of AM Her are systems in which a highly magnetized white dwarf (WD) (B ~ 10^{7−8} G, a.k.a. polars) and a low mass (∼ 0.3 M⊙) secondary star orbit each other. Both stars are thought to be in locked rotation, i.e. they always face each other as they move through their orbits. The orbital distances are small enough (periods of hours) for the secondary star to fill its Roche lobe and an accretion stream emerges from the inner Langrange point towards the more massive WD. The strong WD magnetic field couples to the infalling accretion stream, prevents the formation of an accretion disk, and guides the plasma to the polar regions of the dwarf. The dominant source of luminosity in such a system is created on the poles by the shocked and heated accretion column (‘polar hot spot’). Radiation from the stream, accretion column and surface hot spots ranges over a wide wavelength range: optical lines from heated gas, synchro-cyclotron emission of energetic electrons in magnetic fields, and X-rays from the hot infalling plasma present a complex spectrum. The emission is non-isotropic and shaped by the magnetic field. The light from the very small (several 1000 km) polar hot spot is modified not only by the beaming pattern of the intrinsic radiation processes but also by absorption in the accretion structures and by eclipses. If the orbit takes the WD behind the secondary star we observe an ‘orbital eclipse’, if the poles rotate out of sight we call it a ‘self eclipse’ of the WD. Observing light curves from polars with high time resolution can therefore provide insights into
many details of the geometry and distribution of accreting material and the location and size of the emitting regions.

OBSERVATIONS

RXS J0953+14

The AM Her X-ray binary RXS J095308.6+145841 was discovered in the ROSAT all-sky survey [Beuermann et al. (1999)] as a weak X-ray source and identified [Beuermann and Burwitz (1995)] as an optical binary with magnitudes ranging between 17.3 and $\sim 20$ (see Fig.1). The measurement in 1995 with exposures of 5 minutes was used to determine the orbital period to approximately 6316 sec. Fig. 2 shows the OPTIMA measurement of this CV taken on Jan 11, 2002 at the 3.5m telescope on Calar Alto, Spain. The light curve in 2002 (binning of 1 sec) traces essentially the same characteristic as seen in 1995. The period however, derived from matching the emission profiles in the OPTIMA light curve, is 6245 sec, which is $\sim 71$ sec shorter than the 1995 value. In view of the uncertainties involved in the 1995 measurements we should not conclude that this period change is real. We expect to analyse some more observations of RXS J0953+14 to derive a long-term ephemeris. The sharp drop/rise in intensity at phase $\pm 0.22$, with a constant level in the interval, is most likely caused by a WD self eclipse.
The ROSAT source RXJ0704.2+6203 was identified [Tovmassian et al. (2001)] as a magnetic (B~ 20 MG) CV with an orbital period of $P_{\text{orb}} = 0.06754658 \pm 0.000005$ days = 97.267 min. The system was observed in both high and low states between March 1997 and November 1999. Using the method of Doppler tomography to trace the accretion stream with the H$\beta$ and HeII lines [Tovmassian et al. (2001)] the reference epoch for the inferior conjunction (orbital phase =0) was estimated at $T_0 = 2451141.87 \pm 0.005$ under an assumed inclination angle of 30°, primary mass $M_1 = 0.7 M_\odot$ and mass ratio $q = 0.25$. The OPTIMA measurement shown in Fig. 3 just covers one orbital period of this CV and the light curve measured in 2002 is essentially identical to the curve seen in 1998/99. We also observe a nearly symmetrical hump covering ~ 0.5 in phase. The two epochs of observations are separated by 1145 days (=16950 orbits) and the accuracy of the [Tovmassian et al. (2001)] old ephemeris is insufficient to maintain the phase. The phase shown on Fig. 3 seems to be shifted by +0.42 (i.e. the phase of inferior conjunction would now be found at a value of 1.42). The range of errors on $T_0$ and $P_{\text{orb}}$ result in an ambiguity of 2.7 orbits and we are therefore not yet able to calculate a new and more accurate long term ephemeris.

The light curve of RXJ0704.2+6203 is a typical emission pattern of cyclotron radiation being beamed sideways from the accretion column. The shape and duration of the hump suggests that the spot is being eclipsed by the WD itself in its synchronized rotation with the binary period. The indication of a secondary peak mid-way in the eclipsed phase interval [Tovmassian et al. (2001)], which might indicate a second weak accretion pole in the system, cannot be confirmed with significance in the OPTIMA data. The av-
FIGURE 3. OPTIMA light curve of RXJ0704.2+6203 (1 sec binning). The V magnitudes measured on Jan 12, 1999 [Tovmassian et al. (2001)] are over-plotted as filled circles. The original phase values were shifted by +0.42 to align the two light curves.

average eclipse level drawn in Fig. 3 only gives a similar hint of a slightly elevated level at mid-eclipse.

**EK UMa**

EK UMa was detected as a serendipitous Einstein source 1E 1048.5+5421 in 1979 and identified as a new AM Her system by Morris1987. The optical polarimetry revealed strong circular polarisation mid-way between the two emission peaks. White light photometry and the polarization signal were used by the authors to derive the following ephemeris: $T_0 = 2446418.943(3)$ HJD, $P_o = 0.07948(14)$ days. We applied this ephemeris to the 2002 OPTIMA measurements shown in Fig. 4, well aware of the fact that the large interval between epochs and the errors do not maintain the phase. The light curve of Morris1987 is overplotted and agrees well with the high-time resolved light curve. We do not detect any short time eclipse features.

**DP Leo**

DP Leo, also of AM Her type, was discovered as the first eclipsing polar some 20 years ago as the optical counterpart of the EINSTEIN source E1114+182. It was regularly monitored from ground (optical) and space (opt. and X-rays). The orbital
FIGURE 4. OPTIMA light curve (1 sec binning) of EK UMa (a.k.a. 1E 1048.5+5421). The phase adjusted light curve measured in December 1985 Morris1987 is overplotted. The original phase values were shifted by +1.36 to bring the two light curves into alignment. The phase of maximum circular polarization is thus located at phase=1.36.

FIGURE 5. OPTIMA light curve (1 sec binning) of DP Leo. The ephemeris [Schwope et al. (2002)] which aligns eclipse observations from optical and X-ray data spanning the last 20 years requires a $P$ term.
period is \( \sim 89.8 \) min. It was found to be a two-pole accreting system based on the detection of cyclotron emission lines implying field strengths of \( \sim 30 \) and \( \sim 60 \) MG on the poles. OPTIMA on the 3.5 m telescope of CAHA observed DP Leo on January 10, 2002, starting on UT 02:54:57, duration 156 min, and phased so that two eclipses were completely covered. The observing conditions were good with no significant seeing or transparency variations. The light curve, corrected for airmass and sky background, is shown in Fig. 5. Fitting all recorded mid-eclipse times (superior conjunction) from 1979.9 to 2002.0 Schwöpe et al., 2002 were able to derive a comprehensive ephemeris only if a change in orbital period is admitted. The ephemeris of mid-eclipse times is thus given by \( \text{BJED}_{\text{orb}} = T_0 + P \times E + \frac{1}{2}PP' E^2 \), where \( T_0 = 2448773.215071(18)BJED \), \( P = 0.06236283691(70) \) days, and \( P' = -4.4(4) \times 10^{-12} \text{ss}^{-1} \). The implied spin-down time-scale of the orbit, \( \sim 3.9(4) \times 10^7 \) years, is about 100 times shorter than the angular momentum loss time-scale for gravitational radiation.

In the OPTIMA light curve we discern more features related to the accretion stream. After the initial steep ingress into eclipse a distinct source of fading radiation is still visible, which looks similar to the case of HU Aqr (see next section). The accretion stream is not only visible in emission but also as occulter in the so-called pre-eclipse dip (visible at phase 0.9), again comparable to HU Aqr.

**HU Aqr**

Since 1999 this eclipsing AM Her system was observed regularly with OPTIMA. A sample of representative light curves from 2000, 2001, and 2004 is shown in Fig. 6. From a very bright state in 2000 the source changed in the following years to a faint state, that persists at least until 2007. Clearly visible are the pre-eclipse dips caused by the accretion stream crossing the line of sight to the polar hot spot. The phase of this crossing seems to depend on the brightness of the system: in 2000, during a high-state, the dip precedes the ingress into eclipse by \( \sim 0.128 \) (46°), in 2001, with an intensity about 30% of the year before, the dip is \( \sim 0.09 \) (32°) before ingress. After the steep ingress, when the secondary star eclipses the polar spot of size \( \sim 1000 \) km with a time-scale of 6-7 seconds, emission from the accretion stream is still visible above the limb of the secondary for about 2 minutes. In 2004 in a low-state we cannot detect these absorption/emission features of the stream. The two bumps of emission, centered at phases 0.25 and 0.65 in the 2000 light curve are thought to be the characteristic pattern of synchro-cyclotron radiation perpendicular to the magnetic fields in the accretion column.

**Short optical bursts from HU Aqr**

As an unexpected new phenomenon we detected very short optical outbursts from HU Aqr with a timescale of \( \sim \) seconds. These were first reported from the analysis of observations in July 2000 [Straubmeier (2001)], when the source was in a high-state of optical luminosity. The bursts are already visible in the light curve shown in Fig. 6; a zoom to two of the strongest events in the observation on July 5, 2000 is displayed in the
HU Aqr observed with OPTIMA at SKO

FIGURE 6. OPTIMA light curves (1 sec binning) of HU Aqr measured at the 1.3m telescope of Skinakas Observatory, Univ. of Crete. The top (red) curve was measured on Jul. 5, 2000, the middle (black) curve on Sept. 21, 2001, and the lowest (blue) curve on Jul. 18, 2004

FIGURE 7. HU Aqr short optical outbursts observed on Jul 5 and Jul 8, 2000 during high-state

left panel of Fig. 7, while the right panel shows a similar burst observed on July 8, 2000. At a time resolution of 100ms the bursts appear resolved with a Gaussian profile and a typical width of $0.8 - 1$ sec (FWHM). The bursts are clustered at the orbital phases of the emission maxima and are therefore likely to be related with synchro-cyclotron radiation processes and short injections of accelerated particles produced during the infall of blobs of accreting matter. In Fig. 8 we show two events observed during July 18 and 22, 2004. Here the phase of the bursts is very close to the entry into eclipse (visible in the right panel). The bursts during a low-state of HU Aqr are much smaller than the high-state bursts and their duration is more in the 10-50 seconds range. However the
phenomenon appears to be basically the same.

CONCLUSIONS

We have presented high-time resolution observations of a selection of cataclysmic variables of type AM Her. In these systems the influence of the strong magnetic field of the accreting white dwarf leads to pronounced brightness variations on very short timescales. The accretion stream, which is concentrated on a polar spot of size $\sim 1000$ km is visible in emission as well as in absorption if it passes across the line of sight to the polar spot. Eclipses of the polar spots (sometimes two are detected), which are the dominant source of radiation, can occur either by the rotation of the white dwarf (self eclipse) or by its passing behind the secondary star. We show examples of both types of eclipses. In the truly eclipsing binaries the accurate determination of the mid-phase of eclipse (superior conjunction) allows to derive very accurate ephemerides for the orbits. In DP Leo the ephemeris fitted over about 20 years of X- and optical observations requires a change of orbital period ($a\dot{P}$ term), which is about two orders of magnitude larger than expected from gravitational radiation alone. DP Leo is the first example for this effect, but the long term observations of other eclipsing binaries should allow determination of such accurate ephemerides in the future.

As a new feature, which is only detectable with very high time resolution of typical 0.1 sec, we report on short outbursts from HU Aqr. Although their origin is not yet fully understood, they seem to be closely related to the radiation processes in the lower accretion column.

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