On the ephemeris of the eclipsing polar HU Aquarii. II:
New eclipse epochs obtained 2014 – 2018

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The magnetic cataclysmic variable HU Aquarii displayed pronounced modulations of its eclipse timing. These were intensively modeled and discussed in recent years in the framework of planets orbiting the binary or the Applegate effect. No scenario yielded a unique and satisfactory interpretation of the data. Here we present 26 new eclipse epochs obtained between 2014 and 2018. The steep and continuous decrease of the orbital period observed in the time interval 2010 - 2013 has slowed down sometimes before mid 2016. The new slope in the $(O-C)$-diagram of eclipse arrival times will further constrain physical models of its complex shape.

1 Introduction

HU Aqr is an eclipsing magnetic cataclysmic variable with a 125 min orbital period. When discovered in 1993 as the optical counterpart to the soft X-ray and EUV sources RXJ2107.9-0518/RE2107-05 (Hakala et al. 1993; Schwep\textsuperscript{e} et al. 1993) it was the brightest eclipsing object displaying the most extended eclipse. Those properties triggered broad observational studies to disentangle accretion phenomena and the accretion geometry in a strongly magnetic environment. Particular emphasis was given to model the detailed eclipse structure (see e.g. Schwep\textsuperscript{e} et al. 2001; Vrielmann & Schwep\textsuperscript{e} 2001). Comprehensive X-ray and EUV observations with the ROSAT and EUVE satellites took place between 1992 and 1998 (Schwep\textsuperscript{e} et al. 2001). These studies established the eclipse egress as a fiducial mark to determine the orbital period and a long-term ephemeris and was used by all researches since then (Bours et al. 2014; Gożdziewski et al. 2012, 2015; Qian et al. 2011; Schwarz et al. 2009; Schwep\textsuperscript{e} & Thinius 2014; Vogel et al. 2008). Already this early study from 2001 gave some evidence for deviations of the eclipse egress time from a linear relationship between the cycle counts and the time of arrival. The size of the effect, however, ±5 s, was still compatible with a migration of the accretion spot over the surface of the white dwarf.

Schwarz et al. (2009) were the first to discuss the timing residuals, that were then larger than the size of the white dwarf, in terms of an unseen third body and derived a possible mass of $M_3 = 5M_{\text{Jup}}$ for a planetary companion. Alternative explanations were also discussed, namely Apple-

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Cycle counting follows the convention introduced by Schwoge et al. [2001] and phase zero refers to the first ROSAT observations with full phase coverage back in April 1993.

2 Observations and data reduction

HU Aqr was observed during 1 night in September 2014, 9 nights in 2016 (September and November), 6 nights in 2017 (August, October and November), and 5 nights in July 2018. The equipment used for the observations is exactly the same as in Paper I, hence its description can be kept very short.

All observations were conducted with the 14 inch Celestron reflector of Schmidt Cassegrain type located at Inastars Observatory Potsdam (IAU MPC observer code B15). The telescope is permanently installed at the roof of a one-family dwelling in the suburb of Potsdam, Germany.

All observations were done in white light. An ASTRONOMIK filter was inserted to block strong emission lines at this light-polluted site. Individual images of the field of HU Aqr were recorded with an SBIG ST-8XE CCD as detector. The camera was always used with a 2x2 binning and always with 3 sec integration time on target. The time resolution achieved was 5.2 sec for all runs described here. The start time of each exposure and the exposure time was written into the fits headers. The computer equipment used to control the measurements was typically of the order of 10 ms or less and does not contribute to the error budget.

The format of writing the start times of frames was changed from integer (Paper I) to float (double precision) so that no systematic offset had to be accounted for as in Paper I. A shutter latency of 0.77 s was found and was applied as an additional offset to individual timings of the eclipses.

CCD data reduction followed standard procedures and included bias subtraction and flatfield correction. The analysis of the light curves, i.e. differential photometry with respect to comparison star C (Schwope et al. 1993) was performed with AstroImageJ (Collins et al. 2017). The determination of eclipse egress times followed the scheme described in Paper I. Approximate overall brightness levels at the time of the observations were read from phase-folded lightcurves. The quantity used was the flux ratio of the target with respect to the comparison star (relative flux).

A summary of the observations reported in this paper is given in Table 1 which lists the observation interval per night, the number of frames obtained, and the maximum brightness (relative flux) prior to the eclipse to characterize the accretion state of HU Aqr. For comparison, the maximum relative flux of our observations obtained in 2013 was 0.85 (see Fig. 1 in Paper I).

Table 1  Time-resolved photometric observations of HU Aqr obtained at Inastars Observatory in years 2014, 2016, 2017, and 2018. Given are the observation date, the time interval covered, and the number of frames obtained per night. The accretion state is encoded by giving the maximum relative bright-phase flux prior to eclipse. A dash indicates that only parts of the binary cycle were covered and no unique information about the overall brightness could be extracted from the data.

| Date      | Observation interval | # frames | state     |
|-----------|----------------------|----------|-----------|
| 20140927  | 2456928.278040 – 355020 | 1292     | 0.35      |
| 20160905  | 2457637.428809 – 468838 | 1106     | 0.24      |
| 20160906  | 2457638.295402 – 508805 | 3140    | ""        |
| 20160907  | 2457639.305958 – 391210 | 1418     | ""        |
| 20160908  | 2457640.287360 – 405364 | 1860     | ""        |
| 20160915  | 2457647.293444 – 346335 | 883     | ""        |
| 20160919  | 2457651.309938 – 361001 | 852     | ""        |
| 20160921  | 2457653.298070 – 368882 | 1182     | ""        |
| 20161127  | 2457720.175346 – 216559 | 721     | ""        |
| 20161128  | 2457721.213724 – 248244 | 576     | ""        |
| 20170828  | 2457994.354082 – 441516 | 1477     | 0.66      |
| 20170829  | 2457995.302341 – 418170 | 1955     | ""        |
| 20170715  | 2458042.278304 – 420315 | 2399     | 0.51      |
| 20170716  | 2458043.287405 – 373581 | 1456     | ""        |
| 20171117  | 2458075.188120 – 207617 | 326     | ""        |
| 20171123  | 2458081.265321 – 283137 | 297     | ""        |
| 20180723  | 2458324.354952 – 459001 | 1729     | 0.28      |
| 20180724  | 2458323.361905 – 443743 | 1366     | ""        |
| 20180901  | 2458363.426169 – 440556 | 241     | ""        |
| 20180903  | 2458365.329056 – 347401 | 307     | ""        |
| 20180909  | 2458401.272701 – 310929 | 637     | 0.35      |

3 Analysis and results

3.1 New eclipse epochs

HU Aqr was encountered at intermediate accretion states during all occasions between 2014 and 2018. The brightness of the source as indicated by the maximum brightness in the last column of Table 1 was lower than observed in 2013 where it was found at 0.85. Also the shape of the light curve was found to be variable from being double-humped in the high state to become single-humped at reduced brightness (i.e. at reduced accretion rate). The pre-eclipse dip due to the intervening accretion stream was clearly present only in August and September 2017. The centre phase of the pre-eclipse dip was dependent on the brightness, it was centred 0.12 phase units before eclipse centre in August 2017 and 0.092 phase units before eclipse centre in September 2017.

This behaviour, the morphological changes of the light curves and the phasing of the pre-eclipse dip as a function of the mass accretion rate (brightness of the source) were presented already by Schwoge et al. (2001), who show a collection of light curves in intermediate and high states (their Fig. 3) that appear to be similar to the new data.

The times of individual CCD frames were converted to dynamical time (TDB) in the form of Julian days and corrected to the barycentre of the Solar system using time util-
Table 2  New mid egress times $t_e$ and uncertainties $\Delta t_e$ for the observed eclipses of HU Aqr in 2014 – 2018 from Inastars Observatory. Times are given in BJD(TDB).

| Cycle  | $t_e$  | $\Delta t_e$ |
|-------|-------|-------------|
| 90133 | 2456928.301931 | 0.000030 |
| 90134 | 2456928.388747 | 0.000030 |
| 98300 | 2457637.362839 | 0.000030 |
| 98301 | 2457637.449675 | 0.000030 |
| 98311 | 2457638.317802 | 0.000030 |
| 98312 | 2457638.404711 | 0.000030 |
| 98313 | 2457638.491519 | 0.000030 |
| 98323 | 2457639.356964 | 0.000030 |
| 98334 | 2457640.314718 | 0.000030 |
| 98461 | 2457651.340919 | 0.000030 |
| 98484 | 2457653.337738 | 0.000030 |
| 99254 | 2457720.189440 | 0.000030 |
| 99266 | 2457721.231257 | 0.000030 |
| 102412 | 2457994.368037 | 0.000030 |
| 102423 | 2457995.323057 | 0.000030 |
| 102424 | 2457995.409877 | 0.000030 |
| 102964 | 2458042.292862 | 0.000030 |
| 102965 | 2458042.379694 | 0.000030 |
| 102976 | 2458043.334682 | 0.000030 |
| 103343 | 2458075.197739 | 0.000030 |
| 10413 | 2458081.275169 | 0.000030 |
| 106206 | 2458323.417057 | 0.000030 |
| 106214 | 2458324.458869 | 0.000030 |
| 107666 | 2458363.441204 | 0.000030 |
| 106685 | 2458365.351258 | 0.000030 |
| 107099 | 2458401.294880 | 0.000030 |

Table 3  Mid egress times $t_e$ and uncertainties $\Delta t_e$ for the eclipses of HU Aqr reported by [1993] (Ref. = 1) and [1993] (Ref. = 2) in 1990 and 1992. Times are given in BJD(TDB).

| Cycle  | $t_e$  | $\Delta t_e$ | Ref. |
|-------|-------|-------------|-----|
| -10441 | 2448196.4276095 | 0.000081 | (1), RASS |
| -3792 | 2448773.698672 | 0.000050 | (2) |
| -2377 | 2448896.547498 | 0.000069 | (1) |
| -2376 | 2448896.634617 | 0.000029 | (1) |
| -2364 | 2448897.676286 | 0.000029 | (1) |
| -2354 | 2448898.544836 | 0.000029 | (1) |
| -2353 | 2448898.631466 | 0.000029 | (1) |
| -2342 | 2448899.586464 | 0.000029 | (1) |
| -2341 | 2448899.673463 | 0.000029 | (1) |
| -2181 | 2448913.564856 | 0.000040 | (1) |

Eclipse times given in the mentioned papers refer to the center of the eclipse and were corrected to eclipse egress by adding half the eclipse length, which is 291.7 s for the optical and 292.8 s for the RASS X-ray data. [1993] did not give the original timings of the four eclipses observed by them but they derive an ephemeris based on their data obtained during three nights between May 28 and June 3, 1991, and we use the zero time of their ephemeris.

The recovered eclipse timings with the uncertainties as given in the original papers are listed in Tab.3. They enlarge the database by another 10,000 cycles of the binary, and extend back to the ROSAT all-sky survey in 1990.

### 3.3 Eclipse ephemeris

The newly determined times for the eclipse egress reported in tables 2 and 3 were combined with those reported previously in the literature [2014], [2012], [2015], [2009], and [2001]. The data obtained by [2011] were not included because these were shown to be offset from data obtained at similar epochs for an unknown reason (see the discussion in [2012]). However, the inclusion or omission of those data does not change the overall appearance of the curve but hampers detailed modeling.

The data set now comprises 244 individual eclipse timings, covering 28 years and more than 115,000 orbital cycles of the $P_{\text{orb}} = 125$ min binary. The set is composed of data obtained in the X-ray, the EUV, the UV, and the optical regime. We take all reported measurement uncertainties at face value thus ignoring the small mismatches between those data.

The times of individual eclipse egress were measured by averaging a few data points before and after the egress, computing the half-light intensity and reading the times with a cursor from a graph of the light curve (see Paper I for a graph illustrating the method). Uncertainties of individual eclipse timings were set to half the time resolution achieved, which is 2.6 s at all occasions. All new eclipse measurements are listed in Table 2. In total there are 26 new eclipse epochs, an increase by about 10%.

### 3.2 Eclipse timings from discovery papers

A few more eclipse timings are reported in the literature but were not considered in the latest compilation of those events by [2015]. They can be found in the original discovery papers [1993] and [1993]. We converted the eclipse timings given in those papers to BJD(TDB). Although the early data were obtained with rather low time resolution and have corresponding large error bars their inclusion may turn out to be useful to describe overall trends of the eclipse arrival times with respect to a chosen model.
tematic uncertainty $\sigma$ addressing those kinds of uncertainties). A weighted linear regression to all data points yields the linear ephemeris for the eclipse egress

$$\text{BJD(TDB)} = 2449102.92061290(56) + E \times 0.0868203923138(74)$$  \hspace{1cm} (1)

(numbers in parenthesis give formal 1$\sigma$ uncertainties, reduced $\chi^2 = 20804$ for 242 d.o.f.). It is very obvious and well known that a linear fit does not give a valid description of the data. The residuals are however instructive and are shown in Fig. 1.

The very first observation and main result of this short paper is that the accelerated decrease of the orbital period between 2010 and 2015 has slowed down. The $(O-C)$-diagram displays a new slope that is obvious in the data since year 2016. The slope of the $(O-C)$-diagram seems to be constant since then with an ever decreasing orbital period.

Any constant angular momentum loss will lead to a shorter orbital period and is to be described by a quadratic term in the $(O-C)$-diagram. A quadratic fit of the form $\text{BJD(TDB)} = T_0 + PE + 1/2P\dot{P}E^2$ as a parameterization of such an extra, unspecified loss of angular momentum, reveals a better but still completely unsatisfactory representation of the data:

$$T_0 = 2449102.91983318(68) \hspace{1cm} P = 0.0868620454494(32) \hspace{1cm} \dot{P} = (-1.518 \pm 0.008) \times 10^{-11}$$  \hspace{1cm} (2)

(reduced $\chi^2 = 4087$ for 241 d.o.f.). Such a fit is illustrated with a dashed line in Fig. 1. With respect to this quadratic fit, the $(O-C)$ values are even increasing after cycle 98,000, also with an apparently constant slope.

Fig. 1  Observed minus calculated times of eclipse egress of HU Aqr, according to equation 1. New original data from this work are shown with red rhombs. The dashed line indicates the improvements that are achieved through a quadratic fit (Eq. 2). Short vertical dashes at $(O-C) = -280$ s indicate 5 year intervals beginning Jan 1, 1990.

4 Discussion

The newest additions to the measured set of eclipse timings has revealed another turn in the $(O-C)$-diagram of eclipse arrival times. The change in slope occurred between September 2014 and September 2016, where our data set has a gap. If one subtracts the linear term of the ephemeris according to Eq. 1 one would interpret the behaviour of the $(O-C)$-values as if the decay of the orbital period would go on but with reduced pace (Fig. 1). If a quadratic ephemeris is considered and subtracted from the data, one gets the impression as if the decay of the orbit was completely stopped prior to year 2016. A physical model for a quadratic term, an extra amount of angular momentum loss, would need to be found. Our measured rate of the period change is a factor 80 larger than compatible with the secular change of the orbital period due to gravitational radiation, $\dot{P}_{GW} = -1.9 \times 10^{-13}$ s/s (Bours et al. 2014).

The $(O-C)$ residuals give the impression as if some kind of periodicity might be hidden in the data with a possible period of around 44,000 cycles (3900 days or roughly 10 years). Including a sine-curve in the fitting process does not help removing the large $(O-C)$ residuals, they are not varying periodically. However, the amplitude of such an additional sine-curve is of the order of 25 s.

The deviations in the observed $(O-C)$ diagram of Fig. 1 are much larger than the mentioned X-ray optical offsets and the phase jitter due to instationary accretion.

Goździewski et al. (2015) have intensively studied possible explanations of the $(O-C)$-variations in the framework of Keplerian and N-body formulations of the LTT effect (light travel time) for multiple planets and derive evidence that the LTT hypothesis for the eclipse timing of HU Aqr is unlikely.

Völschow et al. (2016) have studied the size of the Applegate effect for 11 post-common envelope binaries (PCEBs), among them HU Aqr, and find that HU Aqr is one out of four systems whose amplitude of $(O-C)$-variation might still be driven by an Applegate mechanism. Their assessment was based on the size of the $(O-C)$ derived by Goździewski et al. (2015) for their two-planet Keplerian model fit with a quadratic ephemeris. This, as our fit in Eq. 2, has an uncomfortably huge $P$ of unknown origin. Furthermore the derived parameters were found to be highly correlated and led Goździewski et al. (2015) describing their Keplerian model as essentially unconstrained. Nevertheless, Völschow et al. (2016) used the best-fit parameters of the most influential planet ‘C’ from the fit labeled JQ with a semi-amplitude $K_C = 87.7$ s, and period $P_C = 7101$ days, to quantify the size of $(O-C)$ that an Applegate effect should be able to generate. Probably, the order of magnitude of this effect is still valid. Would the periodicity as short as 10 years mentioned above an the size of the effect of order 25 s instead of 87.7 s this would be in favour of the applicability of the mechanism in HU Aqr, because the minimum energy required to drive this mechanism scales with the inverse of the oscillation period.
Whether or not just one explanation, a planetary system or the Applegate mechanism in whatsoever form, or a combination thereof (Bours et al. 2014), or some further not yet considered angular momentum loss mechanism is at work here needs to be seen. Further regular monitoring of the source is of pre-eminent importance. Whatever explanation is preferred eventually, it needs to give an explanation for the large apparent quadratic term in the ephemeris and should also address the occurrence or non-occurrence of (O − C)-variations in systems with very similar parameters as HU Aqr, for example V808 Aur and UZ For, which also need long-term monitoring.

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