

## The orbital ephemeris of HU Aquarii observed with OPTIMA. Are there two giant planets in orbit?

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HU Aqr is an eclipsing CV system hosting a highly magnetic white dwarf orbited by a M4V dwarf with a period of about 125 min. Its orbital ephemeris has been followed with precision since 1993. Regular OPTIMA observations of eclipses of HU Aqr since 1999 can be used to follow the secular changes of the binary orbit. We report new modeling of the orbital ephemeris including recent 2008/2009 observations and find that a model including a linear and quadratic term as well as two sinusoidal oscillatory terms provides the best fit to the observed eclipses. We propose that the sinusoidal variations can be explained by the presence of two giant planets in orbit around HU Aqr.

*High Time Resolution Astrophysics (HTRA) IV - The Era of Extremely Large Telescopes*

*May 5 - 7, 2010*

*Agios Nikolaos, Crete Greece*

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## 1. Introduction

Magnetic cataclysmic variables (CVs, Polars) are interacting close binary systems in which material flows from a Roche lobe filling low mass companion and is accreted by a magnetic white dwarf (WD). Polars (a.k.a. AM Her stars) including a WD with strong magnetic field ( $B \sim 10^7 - 10^8$  G) are a subgroup of magnetic CVs. In these systems the magnetic field of the WD is sufficiently high to lock the system into synchronous rotation ( $P_{\text{spin}} = P_{\text{orb}}$ ) and to prevent the formation of an accretion disk around the WD. The eclipsing system HU Aqr is one of the brightest Polar systems with visual magnitudes ranging from 15 to 18 [1, 2].

To follow the secular changes of the orbital period, the eclipse times of HU Aqr have been observed in optical, UV and X-rays over the last 17 years, including regular OPTIMA (Optical Timing Analyzer) observations since 1999. In total 111 eclipse egress times have been collected, extending the work of Schwöpe et al. (2001), Vogel et al. (2008), and Schwarz et al. (2009) [3, 4, 5]. We have now generated new fits to eclipse egress times in HU Aqr that include recent 2008/2009 observations at Skinakas Observatory, Crete, Greece (Tab. 1). To determine a uniform time stamp for the egress times we fitted the OPTIMA count rates (intensity in a white light band ranging from 450-900 nm [6]) with a sigmoidal function and took the half intensity point as reference (see Fig. 1). Observations and eclipse egress times were converted to Barycentric Julian Ephemeris Dates (BJED). The reference time for eclipse egress epoch zero is 1993 April 25 10:04:56(10) = 2449102.9201(1) BJED, but is also fitted within the range of uncertainty in each individual model.

## 2. Ephemeris Calculation of HU Aqr

### • Linear ephemeris

The baseline linear fit to all observed egress times yields the ephemeris Min I (in BJED), where  $E$  is the orbital epoch. The reduced  $\chi^2$  is  $\sim 141$  and the mean error in the last digits for each term is given in parentheses:

$$\text{MinI} = 2449102.9200653(79) + E \times 0.0868204073(2) \text{ [BJED]} \quad (2.1)$$

The corresponding Observed minus Calculated '(O-C)<sub>1</sub>' values of the linear ephemeris is shown in Fig. 2(a). Assuming that all the O-C values show a roughly sinusoidal variation we applied a least-squares sine fit that reveals the following ephemeris equation with the reduced  $\chi^2$  of  $\sim 38$ :

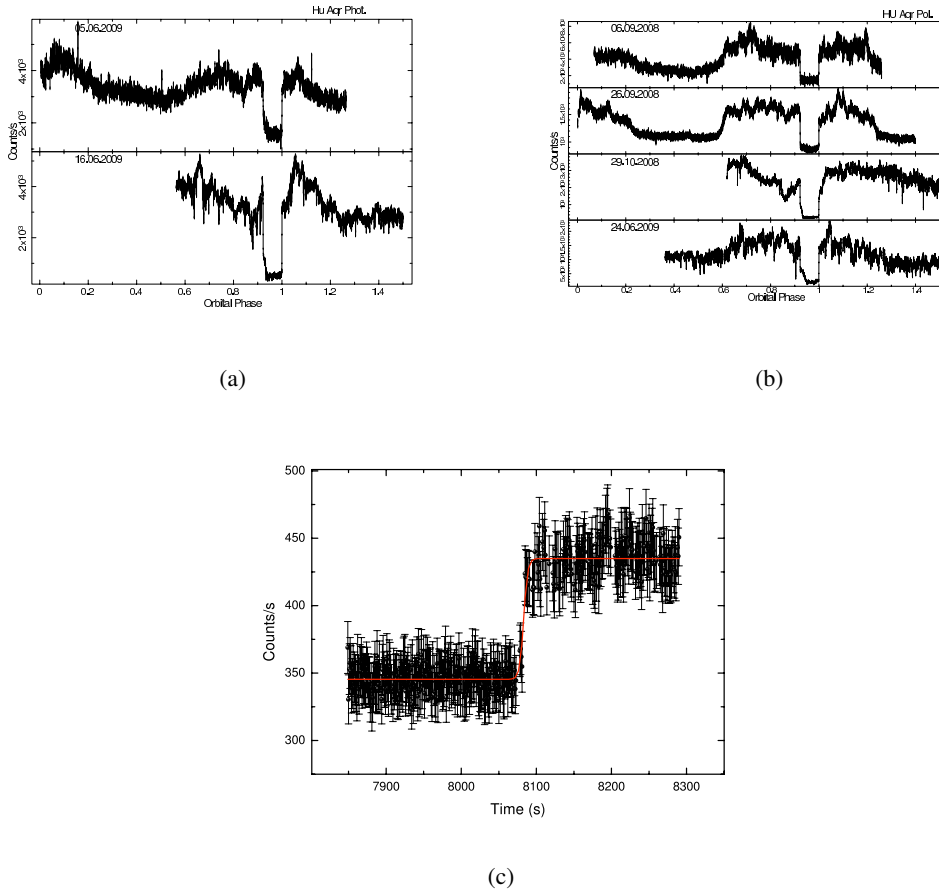
$$(O - C)_1 = 7.75(59) + 13.14(79) \times \sin\{2 \times \pi[E - 9980(569)]/64426(664)\} \text{ [s]} \quad (2.2)$$

This sinusoidal variation with an amplitude of  $13.1 \pm 0.8$  s has a period of  $15.3 \pm 0.2$  years. The remaining residuals of egress times  $(O - C)_2$  w.r.t to the ephemeris including the Eqns. 2.1 and 2.2 are plotted in Fig. 2(b). A second least-squares sine fit to these residual values yields a second cyclic ephemeris with a reduced  $\chi^2$  of  $\sim 11.7$ ,

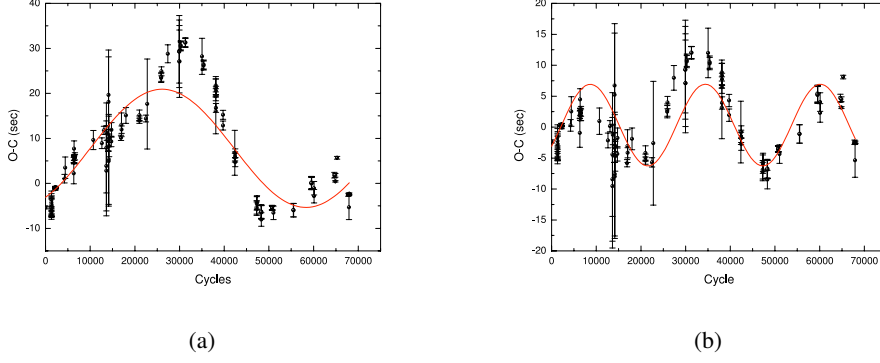
$$(O - C)_2 = 0.324(335) + 6.6(4) \times \sin\{2 \times \pi[E - 2229(239)]/25742(184)\} \text{ [s]} \quad (2.3)$$

Cycle Number	Eclipse Dur. (m)	Egress Time (BJED-2440000+)	$\Delta$ BJED
64657	9.727	14716.46738952	0.00000728
64885	9.738	14736.26244320	0.00000462
64886	9.732	14736.34926361	0.00000188
65265	9.741	14769.25419933	0.00000345
67791	9.711	14988.56255719	0.00000414
67917	9.706	14999.50192896	0.00000159
67918	9.697	14999.58874937	0.000003162
68009	9.735	15007.48940676	0.00000249

**Table 1:** Eclipse egress times of HU Aqr (2008 and 2009).



**Figure 1:** Representative eclipse measurements of HU Aqr in 2008 and 2009, (a) and (b). The reference for phase = 0 is the mid-time of eclipse egress, which is fitted with a sigmoidal function of the form  $y(x) = A_1 + (A_2 - A_1)/(1 + \exp(x_0 - x)/\Delta x)$ .  $A_1$  and  $A_2$  are the levels before and after egress and  $x_0$  'the mid-point' is fitted with an accuracy of 0.6 s in the example for 06 Sep. 2008 (c). The exponential scale  $\Delta x$  was found as  $2.7 \pm 0.5$  s.



**Figure 2:** (a), O–C diagram of HU Aqr with the remaining sine fit (red line). The O–C values have been calculated according to the ephemeris in Eq. (2.1). (b), residual of eclipse egress times w.r.t. an ephemeris including models in Eqns. (2.1) and (2.2) with the remaining fit (red line) according to model in Eq. (2.3).

The remaining sine fit results indicates a cyclical variation with a period of  $6.12 \pm 0.04$  years ( $P = \omega P_{orb} / 365.25$  and  $\omega = 25742(184)$ , where  $P_{orb}$  is the orbital period of HU Aqr) and an semi-amplitude of  $6.6 \pm 0.4$  s. Schwarz et al. (2009) found similar variations with periods of 13 and 6.99 yrs and speculated that these periodic variations might occur because of shape changes induced by a variable magnetic field [5].

#### • Quadratic ephemeris

A weighted quadratic regression to all collected egress times yields the following ephemeris (Min I) with a reduced  $\chi^2$  of  $\sim 91$  and mean error for each term:

$$MinI = 2449102.9200370(73) + E \times 0.086820416(1) - E^2 \times [1.29(17) \times 10^{-13}] [BJED] \quad (2.4)$$

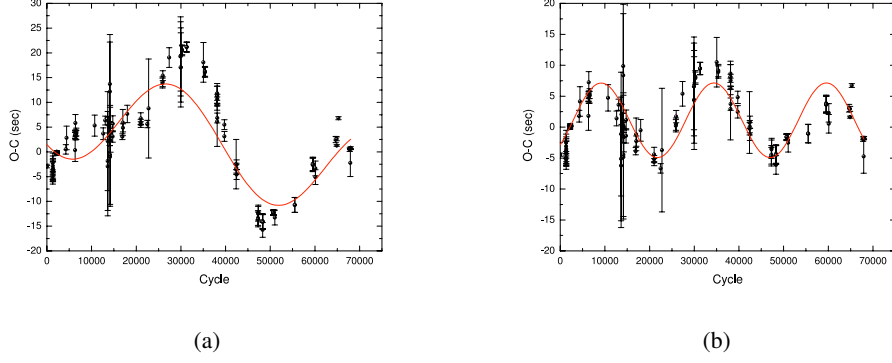
The corresponding residual  $(O-C)_3$  of the quadratic ephemeris is shown in Fig. 3(a). The general trend of  $(O-C)_3$  curve can be described by a combination of a linear and sinusoidal variation. Using a second least-squares fitting on the  $(O-C)_3$  values yields the new ephemeris with the reduced  $\chi^2 \sim 27.6$ ,

$$(O-C)_3 = 9.39(71) - E \times 204(17) \times 10^{-6} + 9.81(67) \times \sin\{2\pi[E - 16167(699)]/46109(897)\} [s] \quad (2.5)$$

The resulting residuals  $(O-C)_4$  after application of Eqns. 2.4 and 2.5 are plotted in Fig. 3(b), and show periodic variation similar to Fig. 2(b). A second least-squares sine fitting to these values yields a new cyclic ephemeris with the reduced  $\chi^2 \sim 6.8$ ,

$$(O-C)_4 = 1.10(\pm 25) + 6.04(\pm 34) \times \sin\{2\pi[E - 2890(\pm 191)]/25196(\pm 146)\} [s] \quad (2.6)$$

This sine fit reveals a periodic oscillation with a semi-amplitude of  $6.0 (\pm 0.3)$  s and a period of  $5.99 (\pm 0.03)$  yr. From a quadratic form  $\Delta T(E) = a + bE + cE^2$ , we can derive  $dP/dE = 2c$  [7]. Thus, an ephemeris curve that displays a quadratic form is proving the period changing at a constant rate with respect to the cycle number  $E$ , and the coefficient of the  $E^2$  term is  $c = P\dot{P}/2$ . This



**Figure 3:** (a), O–C diagram of HU Aqr with the best least squares sinusoidal fit (red line). The O-C differences have been calculated according to the quadratic ephemeris in Eq. (2.4). (b), Residual of eclipse egress times w.r.t. an ephemeris including models in Eqns. (2.4) and (2.5) with the remaining fit (red line) according to model in Eq (2.6).

$c$  coefficient can be determined from the ephemeris curve by a quadratic least–squares solution that represent the observations correctly. Using the relation  $\dot{P} = 2c/P$  and the coefficient of the quadratic term  $c = -1.29(17) \times 10^{-13}$  (Eq. 2.4), we calculated a continuous orbital period decrease of  $\dot{P}_{orb} = (-3.0 \pm 0.4) \times 10^{-12} \text{ ss}^{-1}$ . Schwöpe et al. (2001) calculated a period decrease of  $\dot{P}_{orb} = -10 \times 10^{-12} \text{ ss}^{-1}$  [3], Schwarz et al. (2009) estimated  $\dot{P}_{orb} = (-7 \dots -11) \times 10^{-12} \text{ ss}^{-1}$  [5], and Vogel et al. (2008) obtained  $\dot{P}_{orb} = -13.3 \times 10^{-12} \text{ ss}^{-1}$  [4]. These values are all about 3 times larger than our present value, which now implies an angular momentum loss of about  $-1.3 \times 10^{35}$  erg. Gravitational radiation loss from the binary ( $\sim -1.0 \times 10^{34}$  erg) accounts only for a small fraction of the angular momentum loss, the dominant part is compatible with magnetic braking.

### 3. Discussion

The ephemeris models presented here are characterized by the presence of two sinusoidal variations, a long period one over 11–15 years and an amplitude between 10–13 seconds, and a short period oscillation over about 6 years and 6–7 sec amplitude. Explanations purely intrinsic to the binary system in terms of (i) cyclic movement of the accretion spot on the WD surface due to changes in the accretion flow or (ii) due to orbital period changes caused by a regular stellar activity cycle of the secondary star have been discussed [3, 5] but are not convincingly reconciled with the data. The quality of the sinusoidal variations and the presence of two different periods seems to hint strongly at an explanation in terms of changes in the light travel time due to the presence of smaller ‘planetary’ bodies orbiting the compact binary at large distances. The latest system parameters of the HU Aqr binary were derived by Vogel et al. (2008) and we follow the arguments presented by Qian et al. (2010) for the system of DP Leo, to derive the properties of potential planets around HU Aqr. If we assume that the compact binary and its ‘outer’ satellites move in co–planar orbits (inclination  $85.5^\circ$ , [4]) we conclude that there might be two planets, one with a mass of  $4.42 (\pm 0.28) M_{Jupiter}$  (the mass function  $f(m) = 6.19 (\pm 1.5) \times 10^{-8}$ ) at a distance of  $5.1 (\pm 0.07)$  A.U in a  $11 (\pm 0.2)$  years orbit, and another with a mass of  $4.05 (\pm 0.2) M_{Jupiter}$  ( $f(m) = 4.77 (\pm 0.7) \times 10^{-8}$ ) at distance of  $3.4 (\pm 0.02)$  A.U in a  $6 (\pm 0.03)$  years orbit.

## Acknowledgments

A. Słowikowska acknowledges financial support from the Foundation for Polish Science grant HOM/2009/11B and the Marie Curie European Reintegration Grant PERG05-GA-2009-249168. I. Nasiroglu acknowledges support from the EU FP6 Transfer of Knowledge Project 'Astrophysics of Neutron Stars' (MTKD-CT-2006-042722). G. Kanbach acknowledges support from the EU FP6 Transfer of Knowledge Project 'ASTROCENTER' (MTKD-CT-2006-039965) and the kind hospitality of the Skinakas team at UoC. We thank Arne Rau for discussions on this paper.

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