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A. Slowikowska[1], I. Nasiroglu[2], K. Gozdziewski[3], K. Krzeszowski[4], M. Zejmo[5], P Irawati[6], D. Buckley[7], D. Dimitrov[8] and H. Er[9]

[1]Torun Centre for Astronomy, Nicolaus Copernicus University in Torun, Poland, aga@umk.pl

[2]Astronomy and Astrophysics Dep., Ataturk University, Turkey, inasir@atauni.edu.tr

[3]Torun Centre for Astronomy, Nicolaus Copernicus University in Torun, Poland, k.gozdziewski@umk.pl

[4]Janusz Gil Institute of Astronomy, University of Zielona Góra, Poland, chriss@astro.ia.uz.zgora.pl

[5]Janusz Gil Institute of Astronomy, University of Zielona Góra, Poland, michalzejmo@gmail.com

[6]National Astronomical Research Institute of Thailand, Thailand, puji.irawati@gmail.com

[7]South African Astronomical Observatory, Cape Town, South Africa, dibnob@saao.ac.za

[8]Institute of Astronomy, Bulgarian Academy of Sciences, Sofia, Bulgaria, dinko@astro.bas.bg

[9]Astronomy and Astrophysics Dep., Ataturk University, Turkey, huseyin.er@atauni.edu.tr

Abstract

We investigate the HU Aqr binary eclipse timing to verify if the third-body solutions proposed by Gozdziewski et al. (2015) and in earlier papers are still valid. We aim to test whether the variability seen in (O–C) diagram is due to the presence of one or more circumbinary low-mass companions based on our the most recent and more precise measurements of the mid-egress times. The (O-C) variability can be interpreted as the light time travel effect. With the addition of new observations, we extended the data set presented in Gozdziewski et al. (2015) by approximately three years. Our recent observations indicate a sudden reversing of the previously, long-term decaying (O–C), that took place between May and August 2016. Since none of the previous eclipse ephemeris hold, it reinforces still an unclear hypothesis that the (O-C) variability has not the third-body origin. Moreover, the unusual change of the (O–C) diagram provides a convincing argument for frequent, regular and continuous observations of the HU Aqr - like binaries.

Keywords: Eclipse timing – HU Aqr – Stability of circumbinary planets

1. Introduction

More and more exoplanets around compact binary systems are discovered. Planets orbiting low-mass circumbinary objects are called as the circumbinary planets (CBPs), while their orbits are called "P-type" orbits. The era of the Kepler satellite brought, for example, the discovery of the CBP transiting across the close binary system Kepler-16 AB (Doyle et al. 2011), as well as the longest-period transiting CBP

Kepler-1647 with the orbital period of three years (Kostov et al. 2016). Because the properties of CBPs are different than properties of planets orbiting single stars (Lee et al. 2009), finding the answer to fundamental questions like, how such planets form and evolve, is very timely.

Even before the Kepler satellite era, timing observations of eclipsing binaries provided the evidence a third body orbiting close binary systems, for example, CM Dra (Deeg et al.2008) and HW Vir (Lee et al. 2009). The precision timing of the eclipse minima exhibits deviations between the predicted ephemeris (usually, linear one), and the observed eclipse moments, i.e. abbreviated as observations versus calculations (O–C) hereafter. The times of the eclipses minima appear earlier or later according to the linear or quadratic ephemeris and can result from the gravitational tug of an additional body or bodies in the system. These, sometimes quasi-periodic, variations of the O–C could be interpreted in accord with the Light Travel Time model (aka Rømer effect). This method that relies on long-term monitoring of eclipsing binaries is the most sensitive to massive objects on long-period orbits. Fortunately, rapidly developing observational techniques, as well as hardware development, allow measuring the times of the minima with increasing accuracy. Based on the O–C variations analysis, planets around cataclysmic variables (CVs, e.g. HU Aqr, Gozdziewski et al. 2012, 2015) and post-common envelope binaries (PCEBs), e.g., NSVS 14256825, Nasiroglu et al. (2017), were proposed.

HU Aqr is a close binary system of AM Her type, consisting of a white dwarf and M4 dwarf. The total mass of the binary is 0.98 $M_{\odot}$ (Schwope et al. 2011), while its secondary mass is 0.18 $M_{\odot}$. A long-term stable system of three planets hosted by HU Aqr, with the middle one being on a retrograde orbit, was recently proposed by Gozdziewski et al. (2015). To verify this hypothesis we present 33 new mid-eclipse times of HU Aqr obtained after July 20th, 2014 (see Tab. A1 of Gozdziewski et al. 2015 or the VizieR Online Data Catalogue: HU Aqr planetary system mid-egress moments). New observations extend the observing time span by almost three years. The most recent light curve was acquired on May 30th, 2017. Altogether, the new and archive data span over 24 years. We aim to verify the previous ephemeris over the extended dataset and, if possible, give better constraints of proposed CBPs.

This paper is structured as follows. In Section 2, we present the observations, data reduction and the sigmoid fit used to determine the mid-egress times. Section 3 shows the procedure applied to examine the period variations, while the results are gathered in Section 4. In Sections 5 we discuss and conclude our findings, respectively.

2. Observations

In the time span from 2014 to 2017, we performed observations with three two meter class telescopes, i.e. with the 2-m telescope Ritchey-Chrétien-Coudé reflector at the National Astronomical Observatory in Rozhen (NAO, Bulgaria) equipped with the Princeton Instruments VersArray (NAO-PIVA), with the 2-m Liverpool Telescope at the Observatorio del Roque de Los Muchachos on the Canary island of La Palma (Spain) equipped with the RISE camera (Steele et al. 2004, LT-RISE) and at the 2.4-m Thai National Telescope (TNT) at the Thai National Observatory (TNO, Thailand) equipped with the ULTRASPEC instrument (Dhillon et al. 2014, TNT-USPEC). Additionally, we performed observations of HU Aqr with three smaller telescopes in Turkey. They are as follows: Ritchey-Chrétien type 1.5-m (TUG RTT150) and 1-m (TUG T100) telescopes at the TUBITAK National Observatory (TUG) equipped with Andor DW436 and SI1100 CCD cameras, respectively. The third Turkish telescope used by us is the 0.6-m telescope at the Adiyaman University Observatory (ADYU60) equipped with the Andor iKon-M934 camera (Nasiroglu et al. 2017). A detailed description of the telescopes, CCD camera, CCD data analysis, as well as the time service (time accuracy), can be found in the paragraphs 2.2 and 2.3 of the Gozdziewski et al. (2015).

As an example, we show data taken with the TNT-USPEC on November 18th, 2016. The equation gives the best-fitting sigmoid model (see Sec. 2.3 of Gozdziewski et al. 2015 for detailed description) to the egress of HU Aqr eclipses

$$I(t) = a_1 + \frac{a_2 - a_1}{1.0 - e^{(t_0 - t)} / \Delta_t} \quad (1)$$

is shown in Fig. 1 as a red solid line. In this case, the exposure time of single frame was 2.16 seconds. The sigmoid fit to all data (i.e. mid-egress parts of the light curves) was carried out using the Markov Chain Monte Carlo (MCMC) sampling of the model parameter space. More details about the MCMC and its software applications can be found in Foreman-Mackey et al. (2012). The triangle sigmoid fit parameter correlations and distributions of the data shown in Fig. 1 are presented in Fig. 2.

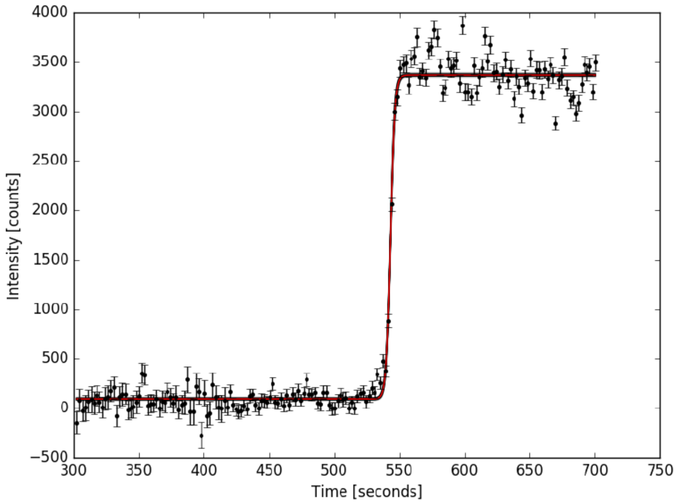

Fig. 1. HU Aqr light curve zoomed around the mid-egress time together with the sigmoid fit (red solid line) given by the Eq. 1. Observations were performed on November 18th, 2016 at the Thai National Observatory (TNT-USPEC). The single frame exposure time was 2.16 s. Each point (black filled circle) corresponds to a single exposure.

We gathered 33 light curves of HU Aqr over almost three years. The mid-egress times calculated from the sigmoid fits are collected in Tab. 1, where the cycle L number, JD TDB, error in days and the observatory/instrument code are given. At this moment we need to comment on Tab. A1 of Gozdziewski et al. (2015). There are two typo errors, i.e. for cycles 81486 and 88985, MJD is 56177.5670248 and 56828.5322517, while it should be 56177.0670248 and 56828.1322517 according to Bours et al. (2014). We also notice that in original Tab. 1 of Bours et al. (2014) there is a typo in MJD for the second observation on September 12th, 2012. It is MJD 56191.060772, and it should be 56181.060772. We corrected all these errors.

3. The ephemeris model

Recently, in Gozdziewski et al. (2012), Marsh et al. (2014); Gozdziewski et al. (2015) an updated and corrected kinematic (Keplerian) formulation of the LTT effect (Irwin 1952) for multiple companions is used. The binary period is shorter than the potential third body orbital period by a factor of more than ~10^5. Therefore the binary system is approximated as a point mass. The eclipse mid-egress times are expressed w.r.t. Jacobi coordinates (Gozdziewski et al. 2012) of the origin at the centre of mass (CM) of the total binary mass (0.98 $M_\odot$, Schwope et al.2011).

The general model accounting for the presence of planetary companions is given by equation:

$$\mathrm{T}_{\mathrm{ephem}}(\mathrm{L}) = \mathrm{t}_0 + \mathrm{LP}_{\mathrm{bin}} + \beta \mathrm{L}^2, \qquad (2)$$

where $T_{ephem}(L)$ is the time of predicted mid-egress at eclipse cycle L, t_0 is the epoch, and β is the derivative of the orbital period P_{bin}, in accord with Hilditch (2001). It has the more general form of Eq. 2

$$\mathrm{T}_{\mathrm{ephem}}(\mathrm{L}) = \mathrm{t}_0 + \mathrm{LP}_{\mathrm{bin}} + \sum_p \zeta_p(t(L)), \qquad (3)$$

where the $\zeta_p(t)$ terms are for the (O-C) deviations induced by gravitational perturbation of the CM by the third bodies ($p = 1, 2, \ldots$ or, in accord with the common convention $p = b, c, \ldots$):

$$\zeta_p(t) = K_p \left[\sin\omega_p(\cos E_p(t) - e_p) + \cos\omega_p\sqrt{1-e_p^2}\sin E_p(t)\right], \qquad (4)$$

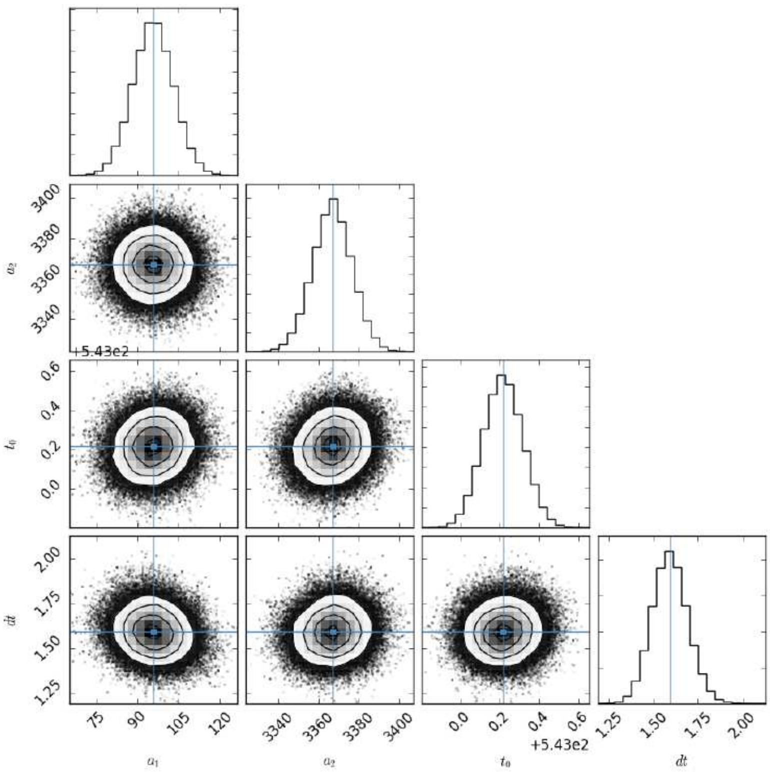

Fig. 2. The triangle sigmoid fit parameter correlations and distribution plots for the data presented in Fig. 1.

where K_p, e_p, w_p are the semi-amplitude of the LTT signal, eccentricity, and argument of the pericenter, respectively for body p. Its orbital period P_p and the pericenter passage T_p are introduced indirectly through the eccentric anomaly $E_p(t)$. In such way we obtained the N-body initial condition of the system with mutually interacting planets.

Table 1. New HU Aqr BJD mid-egress times on the basis of light curves collected with the 2-m telescope at the Bulgarian National Astronomical Observatory (NAO-PIVA), the 2-m Liverpool Telescope (LTRISE), the 2.4-meter Thai National Telescope (TNT-USPEC), as well as with three Turkish telescopes, the TUG 1.5-m (TUGRTT150), the TUG 1-m (TUGT100) and the 0.6-m Adiyaman University Observatory (ADYU60). Archival data are gathered in Tab. A1 of Gozdziewski et al. (2015).

Cycle L	BJD [TDB]	Error (d)	Instrument	Cycle L	BJD [TDB]	Error (d)	Instrument
92691	2457150.3879850	0.0000013	TNT-USPEC	97645	2457580.4954959	0.0000022	TUGT100
93107	2457186.5051720	0.0000014	NAO-PIVA	98208	2457629.3753397	0.0000029	TUGT100
93141	2457189.4571099	0.0000725	TUGT100	98219	2457630.3303643	0.0000029	TUGT100
93153	2457190.4988735	0.0000110	TUGT100	98221	2457630.5039851	0.0000076	TUGT100
93408	2457212.6381020	0.0000016	LT-RISE	98554	2457659.4151565	0.0000044	TUGT100
93546	2457224.6192856	0.0000016	LT-RISE	98575	2457661.2383909	0.0000012	NAO-PIVA
93626	2457231.5649065	0.0000016	LT-RISE	98576	2457661.3252154	0.0000007	NAO-PIVA
93808	2457247.3661694	0.0000330	TUGT100	98610	2457664.2770615	0.0000105	ADYU60
93809	2457247.4529852	0.0000300	TUGT100	98886	2457688.2395041	0.0000066	TUGT100
94544	2457311.2659250	0.0000044	NAO-PIVA	98887	2457688.3263200	0.0000059	TUGT100
94600	2457316.1278293	0.0000006	TNT-USPEC	98978	2457696.2269655	0.0000047	TUGT100
94831	2457336.1833143	0.0000054	NAO-PIVA	98979	2457696.3137833	0.0000036	TUGT100
94898	2457342.0002559	0.0000008	TNT-USPEC	99148	2457710.9864657	0.0000011	TNT-USPEC
94899	2457342.0870782	0.0000024	TNT-USPEC	99149	2457711.0732855	0.0000009	TNT-USPEC
94910	2457343.0420999	0.0000012	TNT-USPEC	99243	2457719.2343737	0.0000037	TUGT100
97633	2457579.4536617	0.0000039	TUGT100	101366	2457903.5539607	0.0000020	TUGRTT150
97644	2457580.4086824	0.0000082	TUGT100				

Obtained O-C diagram (Fig. 3) exhibits a curious change of the eclipse timing. We used our new as well as archive data (see Tab. A1 of Gozdziewski et al. 2015) to verify the previously proposed models of two and three planets orbiting HU Aqr. We found out that new data set spanning over more than 24 years do not match any of the previous CBPs predictions, including the most exotic model of three planets, with the middle one being in the retrograde orbit (Gozdziewski 2015).

4. Discussion and Conclusions

In case of the linear ephemeris, the O–C variations are on the level of 220 seconds (from -160 s to +60 s) over more than 24 years, while in case of quadratic ephemeris it is on the level of 150 seconds (from +60 s to –85 s). The O–C trend shows sudden change between May 5th, 2016 and August 4th, 2016. The O–C amplitude is a critical parameter to estimate the energy required for the Applegate mechanism (Applegate 1992) or more complex Lanza models (e.g., Lanza et al. 1998; Lanza & Rodono, 2004). Recently, Völschow et al. (2016) showed that the O–C variations observed in the HU Aqr system could not be explained with the Applegate (magnetic) cycles and its variants. However, this problem requires further analysis.

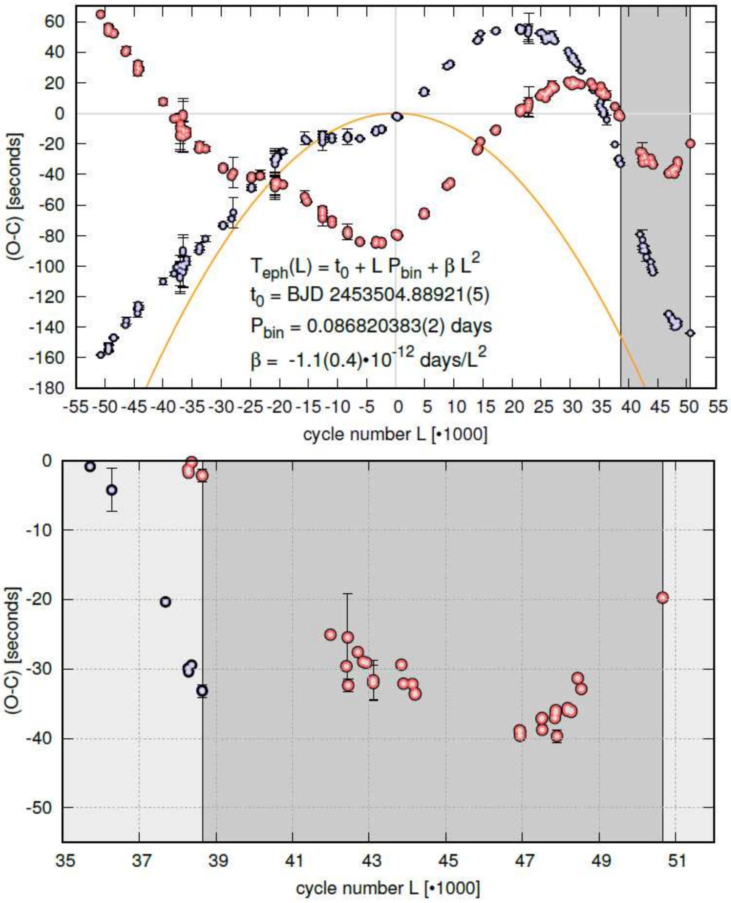

Fig. 3. Upper panel: the O–C diagram of the mid-egress times of HU Aqr . The blue and red filled circles are for the linear and quadratic (additionally plotted as yellow curve) ephemeris, respectively. Labels are for the fitted parameters with the uncertainties at the last significant digit given with a digit in parenthesis. The light-grey shaded region is for the data presented in Gozdziewski et al. (2015), while the dark-shaded region indicates the time span of new data (Tab. 1). Lower panel: the zoom of the O–C diagram for the eclipse cycles between 35000 and 50000. The dip of the O–C trend in the case of quadratic ephemeris is clearly visible. It happened between May and August 2016.

We detected the unusual behaviour of the O-C. Still, an unexplained origin of the variability implies that there is a constant need to monitor HU Aqr. The O-C trend continues and is hardly predictable. All our previous predictions based on the third body hypothesis failed, as indicated by the new set of data. It reinforces the alternative interpretation of the O–C variations observed in this system rather than the presence of CBPs.

At the moment we do not propose other explanation. More extensive observations are necessary to follow the O–C behaviour. We have evidence that in the HW Vir system case, we might face a very similar problem. The O–C variations most likely are not caused by the planetary system because of its strong degeneracy, but they may be of another origin.

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