Mon. Not. R. Astron. Soc. **000**, 000–000 (2014) Printed 10 June 2021 (MN LaTeX style file v2.2)

A stable quasi-periodic 4.18 d oscillation and mysterious occultations in the 2011 *MOST* light curve of TW Hya.*

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Accepted ; Received ; in original form

ABSTRACT

We present an analysis of the 2011 photometric observations of TW Hya by the *MOST* satellite; this is the fourth continuous series of this type. The large-scale light variations are dominated by a strong, quasi-periodic 4.18 d oscillation with superimposed, apparently chaotic flaring activity; the former is most likely produced by stellar rotation with one large hot spot created by a stable accretion funnel while the latter may be produced by small hot spots, created at moderate latitudes by unstable accretion tongues. A new, previously unnoticed feature is a series of semi-periodic, well defined brightness dips of unknown nature of which 19 were observed during 43 days of our nearly-continuous observations. Re-analysis of the 2009 *MOST* light curve revealed the presence of 3 similar dips. On the basis of recent theoretical results, we tentatively conclude that the dips may represent occultations of the small hot spots created by unstable accretion tongues by hypothetical optically thick clumps.

Key words: stars: variables: T Tauri, Herbig Ae/Be, stars: individual: TW Hya, accretion: accretion discs.

1 INTRODUCTION

Although originally considered a mysterious, isolated young K7Ve[1] star (Herbig 1978), TW Hya was later shown to be a genuine Classical T Tauri-type Star (CTTS) (Rucinski & Krautter 1983), one of two stars which still show vigorous accretion in a young (about 8 Myr) association now called TWA (Kastner et al. 1997; Barrado y Navascues 2006). It is the closest (56.4 ± 7 pc, Wichmann et al. 1998) T Tauri-type star to us.

It is observationally well established that the accretion onto magnetic CTTSs occurs through the magnetospheric accretion mechanism, originally developed for accreting neutron stars (Ghosh et al. 1977; Ghosh & Lamb 1979a,b) and thereafter applied for CTTSs (Königl 1991; Cameron & Campbell 1993; Hartmann et al. 1994; Shu et al. 1994). Recent theoretical investigations (Romanova et al. 2004, 2008; Kulkarni & Romanova 2008; Romanova & Kulkarni 2009; Kulkarni & Romanova 2009) of the magnetized-plasma accretion from innermost accretion disks are very relevant to the observational results presented in this paper. They suggest the following picture: For magnetospheres a few times the stellar radius in size (but no less than two stellar radii), the accretion from the surrounding disk can occur in either a *stable*, a *moderately stable* or

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* Based on data from the *MOST* satellite, a Canadian Space Agency mission, jointly operated by Dynacon Inc., the University of Toronto Institute of Aerospace Studies, and the University of British Columbia, with the assistance of the University of Vienna.

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[1] or rather M2.5Ve from a more recent detailed estimate of Vacca & Sandell 2011

an *unstable* regime; The regime of accretion at a given time is controlled by the mass accretion rate and the disc viscosity parameter α. For small values of the viscosity parameter and a low accretion rate, the stable accretion takes the form of steady plasma flows from the inner disc toward the stellar magnetic poles in two funnels encircling the magnetosphere (Romanova et al. 2004). The funnels produce two antipodal banana-shaped hot spots which are almost unmovable on the star. Depending on the inclination angle and the misalignment angle between the stellar rotation axis and the magnetic pole, either one or both hot spots can be visible to an observer during a single stellar rotation. The steady nature of the two accretion funnels results in two stable hot spots so that the flux changes should lead to fairly regular light curves with modulation corresponding to one (or a half) stellar rotation period (Romanova et al. 2004; Kurosawa & Romanova 2013).

Increased disc viscosity and mass accretion rate may lead to an onset of Rayleigh-Taylor (RT) instabilities in the inner accretion disc. The instabilities produce a few equatorial tongues, in which the matter is transferred directly from the disc onto the star. The matter hits the star at slightly lower, moderate latitudes and produces small hot spots (Romanova et al. 2008; Kulkarni & Romanova 2008, 2009). The stochastic behaviour of the tongues and the related hot spots results in progressively more chaotic synthetic light curves as more spots are formed: While at the beginning of the RT instabilities the funnel component still produces a peak at the stellar rotation frequency (though not as steady as in the purely stable case), as time progresses the frequency spectrum starts to show increasingly more additional sporadic peaks produced by rotation into the view of multiple hot spots. This stage is called a *moderately stable* or an *intermediate accretion regime.*

In the fully *unstable regime*, for high values of α and for the mass accretion rate higher by an order of magnitude than in the *stable regime*, the hot spots are created by only a few tongues rotating around the star with angular velocity of the inner disc. It should be noted that in this regime the inner disc comes considerably closer to the star, as compared to its value during the *stable regime* (see Sec. 3.1 in Kulkarni & Romanova 2008). The shape, intensity, number and position of the hot spots change in the inner disc dynamical timescale, the stellar rotation frequency is no longer visible in the frequency spectrum and the synthetic light curves, Fourier and wavelet spectra are very chaotic. Because the tongues move at approximately the inner-disc orbital frequency, the hot spots no longer co-rotate with the star but move in relation to the photosphere. From time to time one or more of the tongues produce a hot spot or a group of spots, which may dominate the overall light changes for a short time – a process leading to drifting quasi-periodic light variations reflecting the inner disc keplerian frequency (Kulkarni & Romanova 2008; Romanova & Kulkarni 2009; Kulkarni & Romanova 2009).

Our *MOST* photometric observations of TW Hya started in the 2007 and 2008 seasons (Rucinski et al. 2008) and continued through the 2009 season (Siwak et al. 2011). During the three seasons, the star showed apparently an irregular behaviour, with flicker-noise characteristics in the Fourier spectrum. Although the star is visible nearly pole-on ($i \approx 15$ deg; see Rucinski et al. 2008 for previous estimates and Donati et al. 2011), no single periodicity dominated even when the observed variations reached about 0.5 mag, occasionally even as much as 1 mag. The long series of observations in 2008 and 2009, analyzed with the wavelet technique, led to an unexpected and significant result: We have firmly established the presence of oscillatory variations which appeared in the accessible range of about 9 to 1.3 days and shortened their periods by typically a factor of two within a few weeks. We originally interpreted this phenomenon as caused by hypothetical hot plasma condensations spirally revolving in the inner accretion disc toward its inner radius. However, these variations could be better interpreted as caused by hot spots produced during the *unstable regime* of accretion[2]. This conclusion finds support in relatively low inner disc temperature (1100-1400 K, Eisner et al. 2006) and a blue colour index of these oscillatory variations which is in qualitative accordance with $T \sim 8000$ K of the variable hot source (see Batalha et al. 2002). Due to the absence of any stable periodicity in the 2008 and 2009 *MOST* light curves, we infer that the strongly *unstable regime* of accretion – solely through fast moving tongues created by RT instabilities – operated in TW Hya at the time.

According to Romanova et al. (2008), episodes of stable and unstable accretion may alternate depending on the accretion rate. We describe here observations of the first clear instance of the *moderately stable accretion regime* in TW Hya which apparently took place in 2011 and was observed by *MOST* during the fourth series of observations which lasted over 43 days (Section 2). We discuss the new results obtained using Fourier and wavelet analyses of these observations in Section 3. The advantage of a better temporal coverage is that it permitted discovery of well defined drops in the star's brightness (Section 4). A summary of the results is given in Section 5.

2 OBSERVATIONS AND DATA REDUCTIONS

The optical system of the *MOST* satellite consists of a Rumak-Maksutov f/6, 15 cm reflecting telescope. The custom broad-band filter covers the spectral range of 350 – 700 nm with the effective wavelength located close to the Johnson *V* band. The pre-launch characteristics of the mission are described by Walker et al. (2003) and the initial post-launch performance by Matthews et al. (2004).

The fourth run of nearly continuous TW Hya observations, utilizing the *direct-imaging* data-acquisition mode, took place over 43.33 days between 24 February and 11 April, 2011, during 545 satellite orbits. Because the star is not in the Continuous Visibility Zone of the satellite and some short time-critical observations of other targets were done in parallel, the effective total time coverage was 16.92 d i.e. 39 percent of the run total length.

The individual exposures were 30 s during the first

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[2] The presence of such hot spots at moderate and even low stellar latitudes is confirmed by spectroscopic observations obtained in March 2008 by Donati et al. (2011), i.e. exactly during the 2008 *MOST* observations. The *MOST* revealed that the light curve and the wavelet spectrum was then dominated by a quasi-periodic feature drifting in its quasi-period from ~ 4 to ~ 3 days (see in Fig.8 in Rucinski et al. 2008).

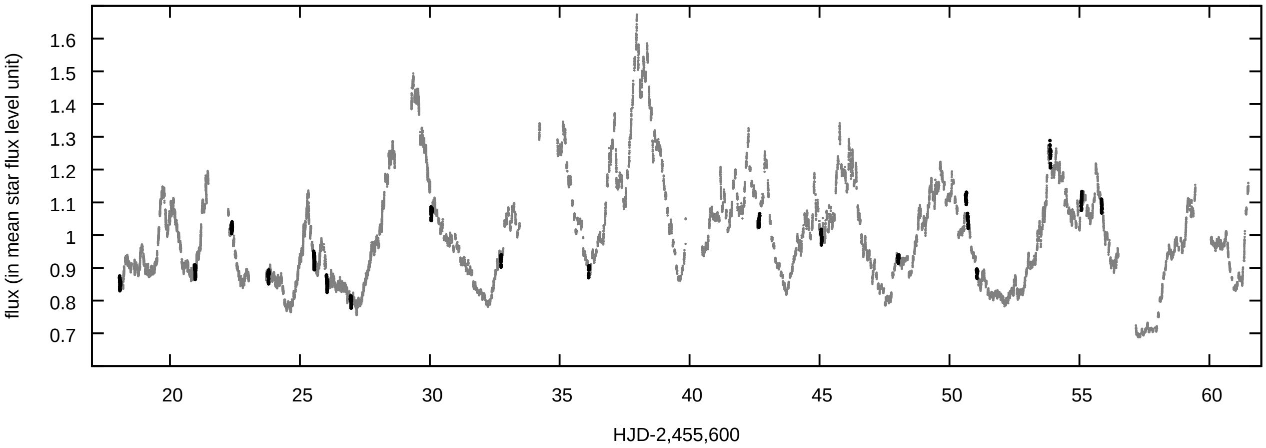

Figure 1. The 2011 light curve of TW Hya in flux units, scaled to unity at the mean brightness level. All individual data points are shown. Observations obtained during *MOST* orbits which showed the "occultations" (see Section 4) are represented by darker points.

part of the run (12.16 days) and 60 s during the second part (31.17 days). For photometric reductions, the *dark* and *flat* calibration frames were obtained by averaging a dozen *empty-field* images specifically taken during the 60 sec run, or – for the case of the 30 sec long exposures – from frames with the target localized far beyond its optimal position due to occasional satellite pointing errors. Aperture photometry of the stars was obtained using the *dark* and *flat* corrected images by means of the DAOPHOT II package (Stetson 1987). As in our previous investigations, a weak correlation between the star flux and the sky background level within each *MOST* orbit was noted and removed; it was most probably caused by a small photometric nonlinearity in the electronic system.

We obtained a well defined light curve for the whole duration of the observations (Fig. 1). The typical error of a single data point is about 0.011 mag. The median value of error (σ) of 545 averaged points (formed for each satellite orbit of 101 min) is 0.0073, with the full range between 0.00014–0.044 in units of the mean normalized flux for the star. Such values of errors are obviously significantly increased due to the variability intrinsic to the star, occurring in time scales shorter then the length of a single *MOST* orbit.
In contrast to the previous *MOST* runs which generally showed erratic behaviour requiring further analysis to reveal regularities in temporal variations, the variations observed in 2011 were surprisingly regular showing roughly equidistant spikes at typical separation of about 4 days. This morphology is new to TW Hya as is the quasi-period which was never observed before to be so persistent.

3 RESULTS OF THE LIGHT-CURVE ANALYSIS

3.1 Fourier analysis

We performed analysis of the light curve in a similar way to Rucinski et al. (2008, 2010) and Siwak et al. (2011). The bootstrap sampling technique permitted evaluation of the mean standard errors of the amplitude $a(f)$, where f is the frequency. We used for the Fourier analysis all 29,230 single data points.

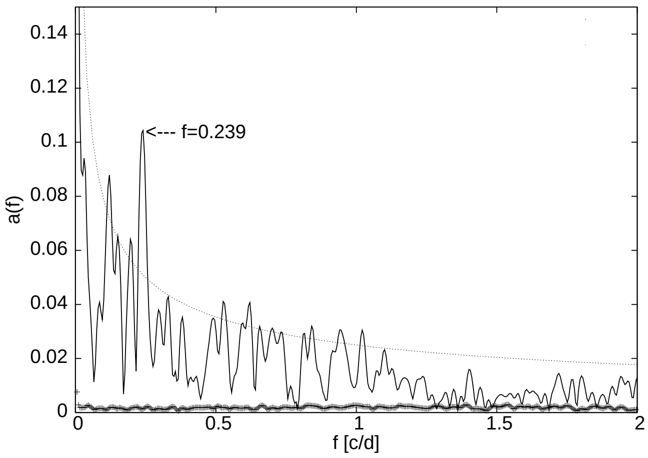

Figure 2. The frequency f spectrum of TW Hya in cycles per day obtained from all 2011 *MOST* observations (the continuos line). A thick black line along the horizontal axis represents errors of amplitude $a(f)$ obtained from the bootstrap sampling technique. The dotted line represents the shape of flickering noise: $a \propto 1/\sqrt{f}$ shown here with arbitrary scaling.

The amplitude spectrum has very similar characteristics to those described in our previous investigations, with dominant flicker-noise $a \propto 1/\sqrt{f}$ characteristics (Fig. 2). Yet, there is one $f = 0.239 \pm 0.014$ c/d significant peak, which – on the basis of the regular variations visible in the full light curve as in Fig. 1 – one might be tempted to assign the 4.18 ± 0.25 day variations to rotation of the star. However, as we know from our previous investigations, TW Hya can demonstrate an amazingly rich spectrum of temporal variations with quasi-periods ranging between 1.3 and 9 days.

3.2 Wavelet analysis

To obtain uniform data sampling required for the wavelet analysis and to remove a few interruptions in the data acquisition (see Sec. 2), we interpolated the 545 mean satellite-

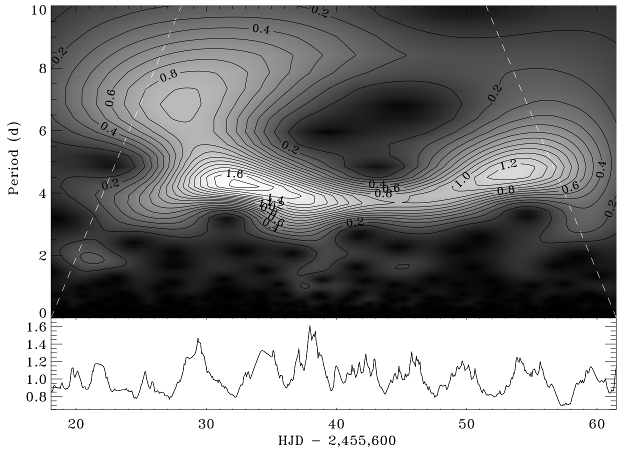

Figure 3. The Morlet-6 wavelet transform of the 2011 TW Hya *MOST* data. The amplitudes of the transform are expressed by grey scale intensities and contours. Edge effects are present outside the white broken lines but they do not affect our conclusions. At the bottom, the *MOST* light curve (in mean star level flux units), re-sampled into a uniformly distributed time-grid with 0.07047 d spacing, is shown.

orbit flux points into a grid of 617 equally-spaced points at 0.07047 day. As we found previously (Rucinski et al. 2008, 2010; Siwak et al. 2011), the Morlet-6 wavelet provided the best match between the time-integrated power spectrum and original frequency spectrum of the star (Fig. 3).

The new results are very different from those obtained during the 2008 and 2009 *MOST* observations:
(1) Starting from $HJD \approx 2,455,627$ the light curve and the wavelet spectrum is dominated by one oscillation of 4.18 d which is strongly visible in the Fourier spectrum in Fig. 2 at $f = 0.239$ c/d.
(2) The oscillation represented by this 4.18 d signal is fairly stable and it does not show any tendency for evolution towards shorter periods as was observed during the previous runs.
(3) Traces of the shortening tendencies may appear in other features in Fig. 3, but they have low significance in comparison to the main, stable oscillation of about 4.18 days.

We conclude that quasi-periodic oscillations with shortening periods do not always play a primary role in TW Hya light variations, contrary to the previous wavelet analysis results. One should keep in mind that the statistics are convincing but not overwhelming: We had only 11 days of observations in 2007 which was too short an interval to analyze with wavelets. The long observations of 2008 and 2009 extending over 46.7 days and 40.3 days showed the very clear trends to shorter periods. It is only the current, fourth run of over 43 days which does not confirm the tendency of the shortening quasi-periodicities which makes it particularly significant in view of recent theoretical investigations.

3.3 Interpretation

When interpreted in terms of the numerical simulations by Romanova et al. (2008), Kulkarni & Romanova (2008) and Kurosawa & Romanova (2013), the events observed during the entire 2011 *MOST* run occurred during a *moderately stable regime* of accretion onto TW Hya. As was described in the Introduction, in this picture, the primary 4.18 d almost stable quasi-periodicity could be produced by rotation-modulation in visibility of a banana-shaped, large hot spot created at the footprint of a steady accretion funnel striking the star close to its magnetic pole. The secondary peaks visible before $HJD \approx 2,455,627$ (and other peaks overlapping with and modulating the primary 4.18 d signal) could be then caused by stochastic accretion tongues producing small hot spots at moderate stellar latitudes. The secondary spots, responsible for the drifting quasi-periodicities, were apparently playing a secondary role in the large scale light variations during the reported here observations (see item no. 3 in Section 3.2). Thus, within the picture presented by Kulkarni & Romanova (2008), the clearly defined onset of accretion through the steady accretion funnel (at about $HJD \approx 2,455,627$) led likely to a drop in the mass-accretion rate by almost an order of magnitude in an interval as short as a week.

We note that Batalha et al. (2002) obtained a similar value of the stellar rotation period of 4.4 ± 0.4 d from their veiling measurements obtained in May and July 1998 and the archival Johnson B-filter photometry of the star. From changes of hot spot projected size, they inferred its extent in latitude to be smaller than 20 deg. Assuming that the spot was a long-term feature created during the *stable* or *moderately stable regime* of accretion, their estimate is in conflict with the theoretical results of Romanova et al. (2004) showing that it must be localized strictly close to the magnetic pole and the stellar rotation axis. The misalignment angle between rotation-axis and magnetic pole for TW Hya seems to be smaller than 10 deg (Donati et al. 2011) so that the apparent movement of the spot and thus light variations should be small. A plausible solution of this discrepancy could be a scenario in which the 4.4 d signal is due to a hot spot (or a group of spots) formed at moderate latitudes by long-term accretion tongues concentrated on one side of the star (Kulkarni & Romanova 2008). However, it is rather unlikely that the latest situation would be stable for over 2 months of Batalha et al. (2002) observations.

The apparent attractiveness of the *moderately stable accretion regime* in explanation of the observed by us light variations in 2011 and in 1998 by Batalha et al. (2002) may, however, be even more challenged. TW Hya exhibits periodic 3.57 d radial velocity variations which were detected spectroscopically by Setiawan et al. (2008) and then confirmed by Huélamo et al. (2008) and Donati et al. (2011). The authors of the two recent publications attributed them to a high-latitude *cold spot* on the stellar photosphere, which remained permanently on the star for at least 2 years; its close vicinity to the major hot spot would then lead to a higher luminance contrast in the polar area of the star. A combination of large hot and cold spots and the low rotation-axis inclination of TW Hya, with added possibilities of strongly differential rotation open up possibilities to explain the observed amplitudes of light variations and the discrepancy between the photometric period of 4.18 – 4.4 days and the spectroscopic period of 3.57 d by adjustment of several parameters in the resulting complex geometry; we prefer to refrain from such an exercise for now.

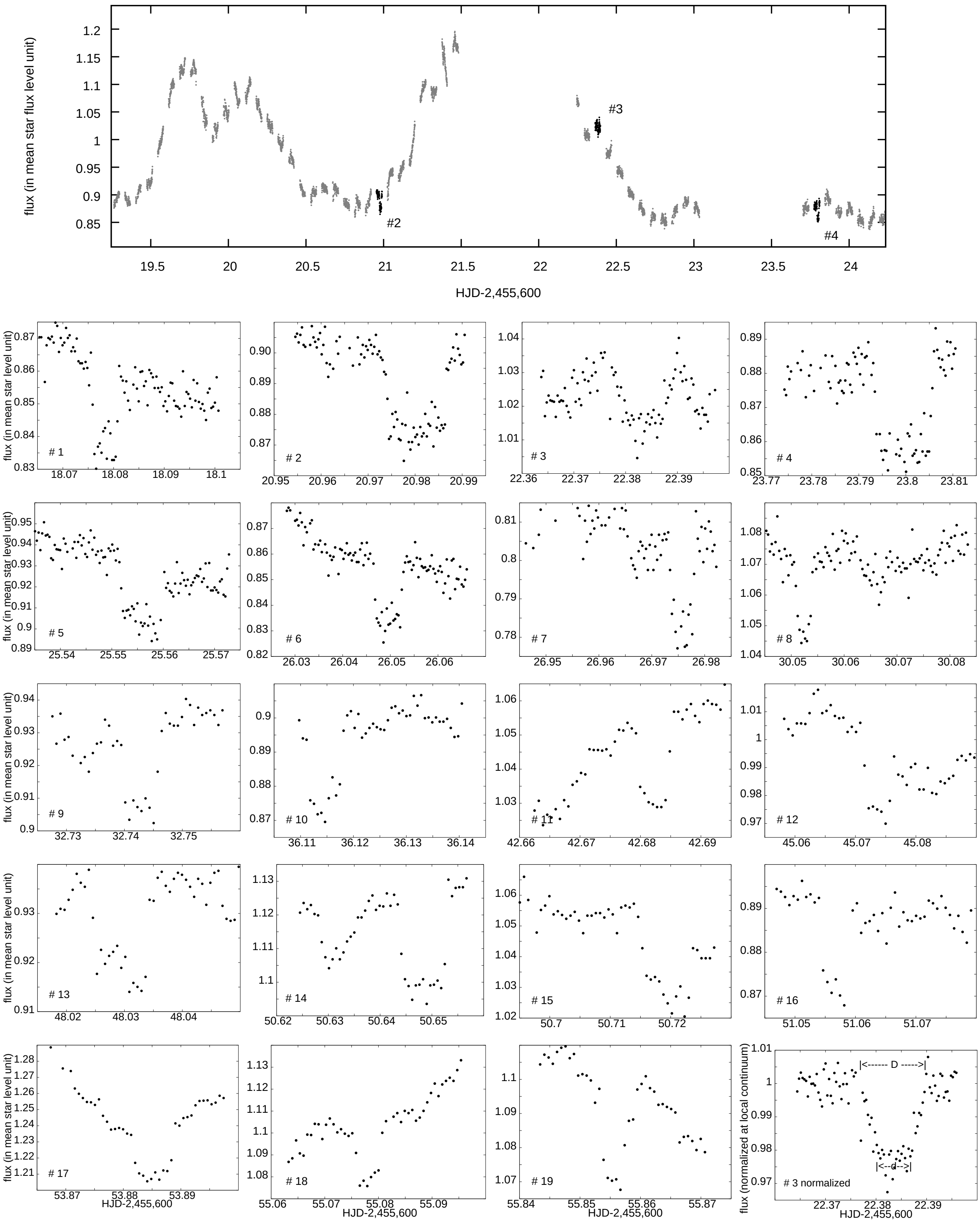

Figure 4. The fragment of the 2011 *MOST* light curve (upper large panel) with occultations #2, 3&4, shown in detail on bottom panels along with all occultations detected by *MOST*. The numbers of occultations are given in the bottom left corner of each figure. The flux is left in normalized flux unit of the star mean brightness, i.e. the same as in Figure 1. Occultations no. 1-8 were observed with 30 s integrations, occultations no. 9-19 with the 60 s integrations. The latest small panel shows the occultation #3 normalized to the local brightness variations, with the horizontal arrows giving the definitions of the outer D and inner d contact duration times.

Table 1. Basic properties of occultations (Fig. 4): the central dip moments hjd_{min}=$HJD - 2,455,600$ estimated from mid-times of inner contacts, the dip depths related to the continuum flux assumed as unity (see Sec. 4), the outer D and inner d contact durations in days (for description see also the last panel in Fig. 4). The errors of first two quantities are given in parenthesis. Typical uncertainties of D and d are about 0.0003 d (0.5 min)

no.	hjd_{min} [d]	depth [%]	D [d]	d [d]
1	18.07835(17)	2.75(59)	0.0061	0.0040
2	20.98028(23)	2.78(48)	0.0158	0.0109
3	22.38364(51)	2.13(38)	0.0137	0.0061
4	23.80000(44)	3.03(41)	0.0134	0.0102
5	25.55569(36)	2.57(46)	0.0093	0.0066
6	26.04961(9)	2.67(43)	0.0072	0.0045
7	26.97578(19)	2.63(56)	0.0055	0.0033
8	30.05245(15)	2.42(23)	0.0039	0.0018
9	32.74260(30)	2.56(32)	0.0078	0.0043
10	36.11464(38)	2.56(31)	0.0082	0.0042
11	42.68241(21)	2.45(11)	0.0068	0.0033
12	45.07359(85)	2.29(14)	0.0063	0.0030
13	48.02946(35)	1.87(35)	0.0119	0.0076
14	50.64864(33)	2.49(20)	0.0102	0.0065
15	50.71951(21)	2.17(34)	0.0099	0.0063
16	51.05640(41)	2.14(24)	0.0064	0.0029
17	53.88521(7)	2.31(18)	0.0077	0.0049
18	55.07829(33)	2.20(23)	0.0067	0.0031
19	55.85564(28)	2.80(10)	0.0072	0.0022

4 THE OCCULTATIONS

4.1 The discovery

Because of TW Hya's location slightly outside of the satellite Continuous Visibility Zone, its *MOST* observations must be interrupted during each orbit. During the 2011 run, the star was observed for typically 40 – 50 minutes during each 101 minute orbit, which makes the current observations very well suited for detection of short-lasting events. This good time coverage (see in Figure 1, and also in Section 2) is important to what we detected and should be contrasted with the previous observations which lasted typically 20 – 40 minutes per orbit. Additionally, to permit multiplexing with other targets, the previous runs included further time limitations with observations of TW Hya during only every second or third satellite orbit. The crucial advantage of the longer than ever before satellite pointing during the 2011 run has led to a discovery of an entirely new phenomenon: the light curve showed 19 short, well defined dips (Figure 4) which we simply call "occultations". As an occultation, we define a flux decrease to a flat or nearly flat bottom and then an increase by the same flux amount which appears similar to eclipses in detached, non-interacting eclipsing binary stars. We require them to be clearly distinguishable from the variety of other quasi-periodic and stochastic, but smooth light variations visible in single-orbit data, even if they take place close in time to the occultations; this point is illustrated in Figure 4.

Table 1 gives the central mean moments of the minima hjd_{min}, their depths and the durations of intervals between the outer D and the inner d contacts. Figure 5 gives the essential characteristics of the occultations such as relative depths, durations and spacings in time.

The *MOST* observations are obtained in one photometric filter so no temperature information is available for interpretation of the phenomenon. Because we do not know what causes the occultations, we can give only a purely heuristic description of their properties:

- From the number of observed 19 occultations with the effective uninterrupted coverage of 16.92 days (see Section 2), we derive the mean rate of occurrence of 1.12 occultation per day.
- Two additional shallow occultations may have been seen as well, but due to the breaks in temporal coverage it is hard to distinguish them from irregular variability intrinsic to the accretion effects. Two more occultations occurred too close to the ends of the *MOST* orbits. These four, ambiguous events are not considered here; their inclusion would increase the frequency to 1.36 occultation per day.
- Most of the events are flat-bottomed and look as though they were caused by total occultations.
- To characterize the occultations in a uniform way, we removed the smooth brightness variations using low-order polynomials fitted to the neighbouring continuum. Their depths measured relatively to the local flux continuum normalized to unity are surprisingly similar and range between 1.87% and 3.03% (see Table 1 and in Figure 5, panel "a").
- In Figure 5, panel "b", we show the distribution of occultation durations. The median value of the full durations is $D = 0.0077 \pm 0.0031$ d (11.1 ± 4.5 min) while the median duration of the total occultation is $d = 0.0043 \pm 0.0025$ d (6.2 ± 3.6 min). The branches, i.e $(D - d)/2$ are very short, on the average lasting 0.00175 ± 0.0006 d (2.5 ± 0.9 min).
- We found four occultations (#2, 3, 4, 13) lasting twice longer than the median duration time (see Table 1). Their branches also last longer in the same proportion. The relation $(D-d)/2 = 0.199(14) \times D$ between the branch durations $(D-d)/2$ and the full durations D is shown in Figure 5, panel "c".
- We do not see any single occultation lasting shorter than 5 minutes, but this may be partly due to the spacing of observations of one minute. Also, due to the specific format of *MOST* data (see in Figure 4) dips lasting longer than about 3/4 of a single *MOST* orbit length (i.e. 35 min) could be undetected; such longer time scales (1-2 h) can be investigated with ground based telescopes.
- Regularity in the distribution of the occultations in time is difficult to characterize because of the breaks in the temporal coverage. Yet, we note that spacings between two pairs of occultations, #8 and #9 (2.69015 d) as well as #13 and #15 (2.69005 d) are identical within the measurement errors (≈ 0.0003 d, Tab 1). However, these four occultations cannot be phased with one linear relation. In contrast to the pair #8 and #9, the occultations forming the pair #13 and #15 look very similar, in that their durations D are comparable and they show the same characteristic shape of light variation. We also note the very similar shapes, depths and durations of the occultations #2 and #4, separated by a similar amount of time (2.81972 d).
- The issue of the regularity of occurrence appears to be crucial in any attempts to find the process producing the occultations. But, even for the time series as uniform as our observations, they have unavoidable gaps in the coverage caused by the location of TW Hya outside of the satellite Continuous Viewing Zone. In order to minimize the effects of

breaks in temporal coverage, we calculated spacings between all possible pairs of occultations and the resulting values were binned into 0.25 d intervals (see Figure 5, panel ”d”). There exists a very well defined primary broad peak, around 2.5 to 3.3 days while the 5.75 d peak may be related to this feature for double spacing. Some secondary concentrations may be present at ~ 1.5 d and ~ 4.5 d but their significance is low. We note that all these features correspond to time scales much shorter than the duration of the *MOST* run and are not affected by its finite duration.

We tested the histogram of spacings between occultations using the Kolmogorov-Smirnov test which compares the respective cumulative distributions. The formal significance for the distribution as in Figure 5 (panel ”d”) being identical to a uniform distribution is only 0.001.

4.2 Have the occultations been seen before?

The large number of occultation events in the 2011 observations of TW Hya leads to an obvious question: Have they been seen before and we simply overlooked them in our 2007, 2008 and 2009 *MOST* observations? The accuracy of 2007 data was too small to allow for their detection. Although the 2008 and 2009 runs lasted 46.7 and 40.3 days, their effective strictly continuous time coverages was only 6.96 and 4.62 d, respectively. In this respect, the 2011 run with the effective coverage of 16.92 days was by far more conducive for detection of the occultations. Nevertheless, taking into account the effective coverage time ratios, we should have seen a few occultations (i.e. 8 and 5, respectively) in the older data.

Although several brightness drops in the 2008 data could potentially be similar to the occultations discussed here, none has such a well defined shape as those observed in 2011. Three possible occultations appear to exist in the 2009 *MOST* observations at $HJD - 2,454,900 = 6.700(1), 6.914(1)$ and $28.473(1)$ (see Figure 6). Their depths are 1.0%, 0.7% and 2.3%, respectively, but only the last event is as well defined as any of the 2011 occultations. We infer that perhaps due to different conditions producing the occultations, their shape, depth and occurrence rate can evolve from season to season.

Other T Tauri stars may have also shown the occultations. The rapid brightness drops, but of very different depths and durations were noted in high speed photometry of the Classical T Tauri-type star DD Ser, Verlyuk (1995) where much deeper, 0.3-0.7 mag dips lasted only 4-5 sec. A single 1.2 mag, very brief (1.7 sec) dip was also observed in AB Aur, a Herbig Ae star. For the latter star the inclination angle of the accretion disc is 29.8 ± 1.3 deg (Hashimoto et al. 2011), which is similar to the nearly pole-on disk in TW Hya.

4.3 What is occulted and what is causing the occultations?

Debes et al. (2013) suggest that a planetary formation process is occurring in the TW Hya accretion disc. However, because of the pole-on orientation of the rotation axis of the star and of the inner disc visible in infrared light (Krist et al. 2000; Potter 2005), one would not expect to observe planets forming close to the disc plane and passing in front of the star. On the other hand, the range of planetary-orbit inclinations in young stars may be surprisingly large. We note the case of the weak-lined T Tauri-type star CVSO 30 which was shown by van Eyken et al. (2012) to have a possible planet transiting for $i = 62 \pm 4$ deg.

Although the occultation depths of 2-3% in Table 1 are similar to those caused by transits of giant planets, the short branch durations of about 2 – 3 minutes and the semi-regular incidence of the occultations indicate that the occulted source is not the star itself but must have dimensions of a sizeable fraction of the stellar radius. If the occultations were due to the transits in front of TW Hya, the occulting bodies would have to be large, about 0.15 of the diameter of the star. Moreover, even if a hypothetical planet would orbit the star on polar orbit with a semi-major axis similar to the inner accretion disc radius of 12 $R_\odot$ (Eisner et al. 2006), the expected transit duration times for the 0.4-0.7$M_\odot$ star (Vacca & Sandell 2011) would be about 2-3 hours.

Through process of elimination, we conclude that the occulted sources are most likely hot regions of small, yet finite dimensions. These could be the hot spots localized at footprints of accretion tongues created through RT instabilities and/or sources of numerous, strong emission lines observed in a spectrum of the star. The typical angular dimensions of the hot regions, as seen by the occulting body must be very small, roughly $\simeq 0.0006$ rad (0.03 deg), for the assumed 2.5 minutes of the branch duration and 3 days for their characteristic reappearance time indicated by the main broad peak in Figure 5 (panel ”d”); Presumably the inner disc and the stellar rotational frequencies comprise the most natural ”clocks” determining temporal occurrence of the occultations.

We see no dependence between the eclipse depths and their durations (Figure 5, panel ”a”) so that the eclipsed sources probably had very similar sizes and brightnesses during the entire 2011 *MOST* run. If these sources would have an additional freedom to move, as predicted for hot spots created through RT instabilities rotating around the star with the inner disc rotational frequency, no strict periodicity would be expected between the eclipse events. This scenario could explain why the characteristic reappearance time of the occultations of 2.6-3.2 d (Figure 5, panel ”d”) is shorter than the stable 4.18 d main signal; it could also explain the occurrence of two pairs of occultations separated by the same amount of time (2.69 d) and the third one separated by 2.81 d, which consists of dips with very similar shapes and duration times (see in Fig. 4 and in Section 4.1).

Similarly to speculations on the nature of the occulted sources, we can offer only speculations on the nature of the occulting bodies. In Figure 5, panel ”c”, we note that the branch and eclipse durations are positively correlated. This is a very important feature which may be interpreted as indicating several occulting bodies positioned at different distances from the star. These could be free-floating dark clumps, perhaps elements of TW Hya’s Oort cloud, representing a more advanced stage of ”dusty traps” suggested on the basis of ALMA observations of Oph IRS-48 by van der Marel et al. (2013). But they could be also small optically thick plasma condensations (if not the accretion stream itself) levitating in a magnetic field of the steady accretion funnel encircling the stellar-disc magnetosphere and acting as natural screens for the hot spots created at low or moderate latitudes of the star. This scenario could explain

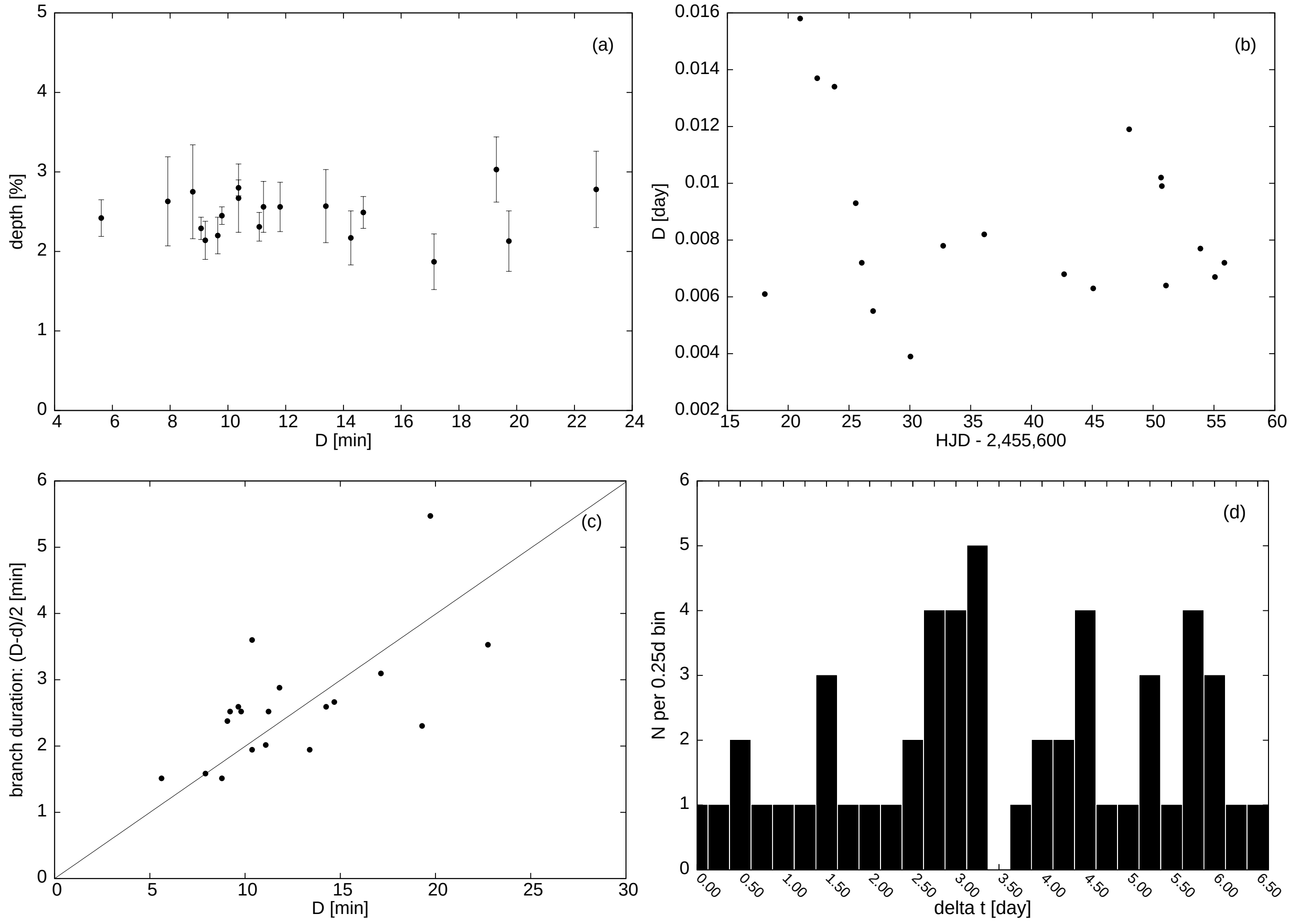

Figure 5. The figure presents relations between various characteristics of the occultations: (a) The relation between the occultation durations D and their relative depths (in percent), (b) The distribution of outer contact durations D in time, (c) The relation (a straight-line fit) between the durations D and the branch durations $(D-d)/2$: $(D-d)/2 = 0.199(14)D$, and (d) The histogram of spacings between all available pairs of occultations.

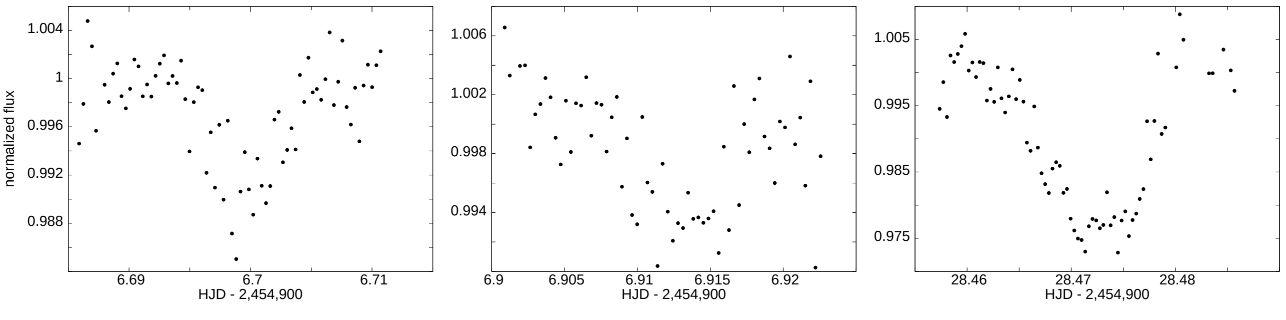

Figure 6. Possible occultations in the *MOST* 2009 light curve of TW Hya, i.e. those obtained two years before the discovery observations reported here. Only the last two events fully meet definition of an occultation as given in Section 4.1.

the high occultation rate in 2011, when the *moderately stable regime* of accretion operated in the star.

5 SUMMARY

The results of the 2011 *MOST* satellite observations of TW Hya are exceptional when compared with the results from the 2007, 2008, and 2009 seasons. While the general light variations retained the general characteristics of flicker noise with amplitudes scaling as: $a \propto 1/\sqrt{f}$ (see also Rucinski et al. 2008; Siwak et al. 2011), the 2011 season variations did not show any obvious period shortening of the oscillation features. This time, the Fourier and wavelet spectra are dominated by a single almost stable oscillation with a period of 4.18 ± 0.25 days. We propose that the dominant oscillation is due to rotational modulation produced by a single, large hot spot formed close to the magnetic pole, at the footprint of the accretion funnel which can originate only during the *stable* or *moderately stable regime* of accretion (Romanova et al. 2004; Kulkarni & Romanova 2009). Within this framework, the fairly stable 4.18 d signal could represent the true rotational period of the star (see also Batalha et al. 2002; Kurosawa & Romanova 2013). It is not clear at this time how the 4.18 d periodicity relates to the previously observed 3.57 d spectroscopic period.

A new phenomenon has been detected in the light curve of TW Hya consisting of numerous relatively short-duration (10 – 20 min), 2 – 3% deep drops in brightness which we call occultations. Their short branches, lasting typically about 2.5 minutes indicate finite dimensions of the occulted source(s). Although without any temperature information we are unable to firmly interpret the observed phenomenon, we suggest that these can be due to occultations of small hot spots on the star, created at moderate latitudes at the footprints of a few accretion tongues produced through the Rayleigh-Taylor instabilities. The obscuring body could be some dark, free-floating condensed clumps orbiting the star on highly inclined orbits beyond the magnetosphere or levitating in magnetic fields optically thick plasma condensations within the accretion funnel. It is expected that multicolour and spectral, high-cadence observations of TW Hya will bring crucial information about the temperature of the occulted regions to provide more firm interpretation for our discovery.

ACKNOWLEDGMENTS

MS is grateful for the Polish National Science Centre grant 2012/05/E/ST9/03915, fully supporting his research.

The Natural Sciences and Engineering Research Council of Canada supports the research of DBG, JMM, AFJM, and SMR. Additional support for AFJM comes from FQRNT (Québec). RK is supported by the Canadian Space Agency and WWW is supported by the Austrian Science Funds (P22691-N16).

This research has made use of NASA's Astrophysics Data System (ADS) Bibliographic Services.

Special thanks are also due to an anonymous referee for highly useful suggestions and comments on the previous version of the paper.

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