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

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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 probably produced by stellar rotation with one large hotspot created by a stable accretion funnel, while the latter may be produced by small hotspots, created at moderate latitudes by unstable accretion tongues. A new, previously unnoticed feature is a series of semiperiodic, well-defined brightness dips of unknown nature, of which 19 were observed during 43 d of our nearly continuous observations. Re-analysis of the 2009 *MOST* light-curve revealed the presence of three similar dips. On the basis of recent theoretical results, we tentatively conclude that the dips may represent occultations of the small hotspots created by unstable accretion tongues by hypothetical optically thick clumps of dust.

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

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 that 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, Lamb & Pethick 1977; Ghosh & Lamb 1979a,b) and thereafter applied to CTTSs (Königl 1991; Cameron & Campbell 1993; Hartmann, Hewett & Calvet 1994; Shu et al. 1994). Recent theoretical investigations (Romanova et al. 2004; Romanova, Kulkarni & Lovelace 2008; Kulkarni & Romanova 2008, 2009; Romanova & Kulkarni 2009) of the magnetized-plasma accretion from the innermost accretion disc 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 disc can occur in a *stable*, a *moderately stable* or 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 towards the stellar magnetic poles in two funnels encircling the magnetosphere (Romanova et al. 2004). The funnels produce two antipodal banana-shaped hotspots, 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 hotspots can be visible to an observer during a single stellar

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

rotation. The steady nature of the two accretion funnels results in two stable hotspots, so that the flux changes should lead to fairly regular light-curves with modulation corresponding to one (or half of a) stellar rotation period (Romanova et al. 2004; Kurosawa & Romanova 2013).

Increased disc viscosity and mass accretion rate may lead to the onset of Rayleigh–Taylor (RT) instabilities in the inner accretion disc. The instabilities produce a few equatorial tongues, in which matter is transferred directly from the disc onto the star. The matter hits the star at slightly lower, moderate latitudes and produces small hotspots (Romanova et al. 2008; Kulkarni & Romanova 2008, 2009). The stochastic behaviour of the tongues and the related hotspots results in progressively more chaotic synthetic light-curves as more spots are formed: while at the onset of RT instabilities the funnel component still produces a peak at the stellar rotation frequency (although one that is not as steady as in the purely stable case), as time progresses the frequency spectrum starts to show an increasing number of additional sporadic peaks produced by the multiple hotspots that come into view as the star rotates. This stage is called the *moderately stable* or *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 hotspots are created by only a few tongues rotating around the star with the 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 with the case during the *stable* regime (see section 3.1 in Kulkarni & Romanova 2008). The shape, intensity, number and position of the hotspots change on the inner disc dynamical time-scale, 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 orbital frequency of the inner disc, the hotspots no longer corotate with the star but move in relation to the photosphere. From time to time one or more of the tongues produces a hotspot 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, 2009; Romanova & Kulkarni 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 an apparently irregular behaviour, with flicker-noise characteristics in the Fourier spectrum. Although the star is visible nearly pole-on ($i \approx 15^\circ$; 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, analysed with the wavelet technique, led to an unexpected and significant result: we have firmly established the presence of oscillatory variations that appeared in the accessible range of about 9 to 1.3 d 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 towards its inner radius. However, these variations could be better interpreted as being caused by hotspots produced during the *unstable* regime of accretion.[2] This conclusion finds support in the relatively low inner disc temperature (1100–1400 K, Eisner, Chiang & Hillenbrand 2006) and the blue colour index of these oscillatory variations that is in qualitative agreement with $T \sim 8000$ K for the variable hot source (see Batalha et al. 2002). Owing to the absence of any stable periodicity in the 2008 and 2009 *MOST* light-curves, we infer that the strongly *unstable* regime of accretion – acting solely through fast-moving tongues created by RT instabilities – operated in TW Hya at that time.

According to Romanova et al. (2008), episodes of stable and unstable accretion may alternate, depending on the accretion rate. In Section 2 we describe observations of the first clear instance of the *moderately stable* accretion regime in TW Hya, which apparently occurred in 2011 and was observed by *MOST* during the fourth series of observations, which lasted over 43 d. We discuss the new results obtained using Fourier and wavelet analyses of these observations in Section 3. The advantage of the better temporal coverage is that it permitted the discovery of well-defined drops in the brightness of the star, as detailed in 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 d between 2011 February 24 and April 11, 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 performed in parallel, the effective total time coverage was 16.92 d, namely 39 per cent of the run total length.

The individual exposures were 30 s during the first part of the run (12.16 d) and 60 s during the second part (31.17 d). For photometric reductions, the *dark* and *flat* calibration frames were obtained by averaging a dozen empty-field images specifically taken during the 60-s run, or – for the case of the 30-s exposures – from frames with the target localized far beyond its optimal position owing 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 probably caused by a small photometric non-linearity 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 and 0.044 in units of the mean normalized flux for the star. Such values of errors are obviously significantly increased owing to the variability intrinsic to the star, occurring on time-scales shorter then the length of a single *MOST* orbit.

[2] The presence of such hotspots at moderate and even low stellar latitudes is confirmed by spectroscopic observations obtained in 2008 March by Donati et al. (2011), i.e. during the time of the 2008 *MOST* observations. The *MOST* observations 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 d (see fig. 8 in Rucinski et al. 2008).

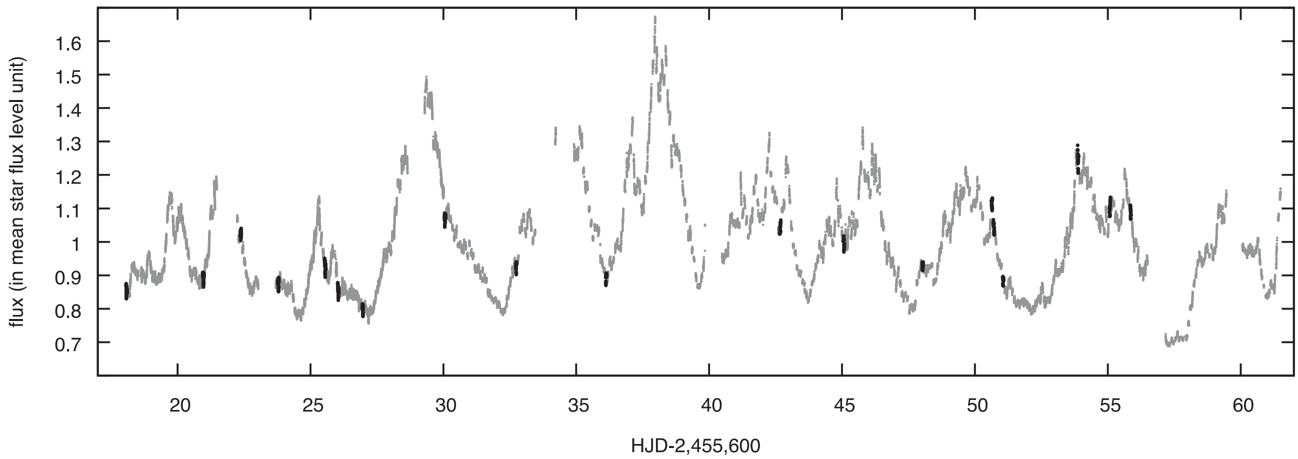

Figure 1. The 2011 light-curve of TW Hya in flux units, scaled to unity at the mean brightness level. All individual data points are shown. Observations obtained during *MOST* orbits that showed 'occultations' (see Section 4) are represented by darker points.

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 a typical separation of about 4 d. This morphology is new to TW Hya, as is the quasi-period, which was never previously observed to be so persistent.

3 RESULTS OF THE LIGHT-CURVE ANALYSIS

3.1 Fourier analysis

We performed the 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. For the Fourier analysis we used all 29 230 single data points.

The amplitude spectrum has very similar characteristics to those described in our previous investigations, with dominant flicker-noise characteristics, $a \propto 1/\sqrt{f}$ (Fig. 2). There is, however, one significant peak with $f = 0.239 \pm 0.014$ c/d. On the basis of the regular variations visible in the full light-curve in Fig. 1, one might be tempted to attribute the 4.18 ± 0.25-d variations caused by the 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 d.

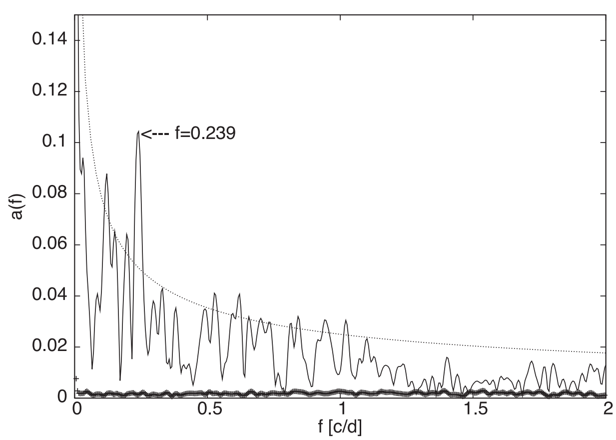

Figure 2. The frequency (f) spectrum of TW Hya in cycles d^{-1} obtained from all 2011 *MOST* observations (the continuous line). The thick black line along the horizontal axis represents errors of the amplitude $a(f)$ obtained from the bootstrap sampling technique. The dotted line represents the shape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

3.2 Wavelet analysis

To obtain the uniform data sampling required for the wavelet analysis and to remove a few interruptions in the data acquisition (see Section 2), we interpolated the 545 mean satellite-orbit flux points onto a grid of 617 points spaced equally at 0.07047d. 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 the original frequency spectrum of the star (Fig. 3).

The new results are very different from those obtained during the 2008 and 2009 *MOST* observations:

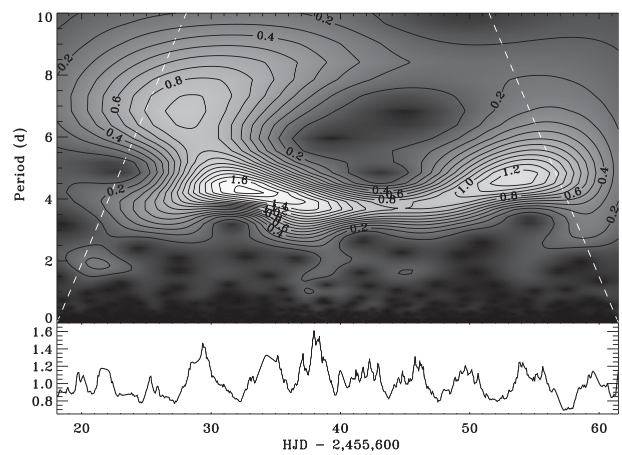

Figure 3. The Morlet-6 wavelet transform of the 2011 TW Hya *MOST* data. The amplitudes of the transform are shown by grey-scale intensities and contours. Edge effects are present outside the white broken lines but do not affect our conclusions. The bottom panel shows the *MOST* light-curve (in mean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

(1) Starting from HJD ≈ 2 455 627, the light-curve and the wavelet spectrum are 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 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 with the main, stable oscillation of about 4.18 d.

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. It should be kept in mind that the statistics are convincing but not overwhelmingly so: we had only 11 d of observations in 2007, which was too short an interval to analyse with wavelets. The long observations of 2008 and 2009 extending over 46.7 and 40.3 d showed very clear trends to shorter periods. It is only the current, fourth run of over 43 d that 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 scenario, the primary 4.18-d almost stable quasi-periodicity could be produced by rotation-modulation in the visibility of a banana-shaped, large hotspot created at the footprint of a steady accretion funnel striking the star close to its magnetic pole. The secondary peaks visible before HJD ≈ 2 455 627 (and other peaks overlapping with and modulating the primary 4.18-d signal) could then be caused by stochastic accretion tongues producing small hotspots 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 observations reported here (see item number 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 ≈ 2 455 627) probably led 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 1998 May and July and the archival Johnson *B*-filter photometry of the star. From changes in the hotspot projected size, they inferred its extent in latitude to be smaller than 20°. 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 the rotation axis and magnetic pole for TW Hya seems to be smaller than 10° (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 caused by a hotspot (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 unlikely that the latest situation would be stable for the period of more than 2 months of the Batalha et al. (2002) observations.

The apparent attractiveness of the *moderately stable* accretion regime as an explanation of the light variations observed by us in 2011 and in 1998 by Batalha et al. (2002) can be challenged even further. 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 latter papers attributed the variations to a high-latitude *cold spot* on the stellar photosphere, which remained permanently on the star for at least 2 yr; its close vicinity to the major hotspot 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 d and the spectroscopic period of 3.57 d by the adjustment of several parameters in the resulting complex geometry; we prefer to refrain from such an exercise for now.

4 THE OCCULTATIONS

4.1 The discovery

Because of TW Hya's location slightly outside the satellite continuous visibility zone, its *MOST* observations are interrupted during each orbit. During the 2011 run, the star was observed for typically 40–50 min during each 101-min orbit, which makes the current observations very well suited for the detection of short-lasting events. This good time coverage (see Fig. 1, and also Section 2) is important and should be contrasted with the previous observations, which lasted typically 20–40 min per orbit. Furthermore, in order 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 benefit of this longest ever satellite pointing during the 2011 run was that it led to the discovery of an entirely new phenomenon: the light-curve showed 19 short, well-defined dips (Fig. 4), which we simply call 'occultations'. We define an occultation as a flux decrease to a flat or nearly flat bottom and then an increase by the same flux amount. This pattern is similar to that which occurs in eclipses in detached, non-interacting eclipsing binary stars. We require the occultations to be clearly distinguishable from the variety of other quasi-periodic and stochastic, but smooth, light variations visible in single-orbit data, even if these variations take place close in time to the occultations; this point is illustrated in Fig. 4.

Table 1 gives the central mean moments of the minima $hjd_{\min}$, their depths and the durations D and d of intervals between the outer and the inner contacts, respectively. Fig. 5 gives the essential characteristics of the occultations, such as relative depth, duration 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 the causes of the occultations, we can give only a purely heuristic description of their properties, as follows.

(1) From the number (19) of observed occultations with effective uninterrupted coverage of 16.92 d (see Section 2), we derive a mean rate of occurrence of 1.12 occultations per day.

(2) Two additional shallow occultations may also have been seen, but owing to the breaks in temporal coverage it is hard to distinguish

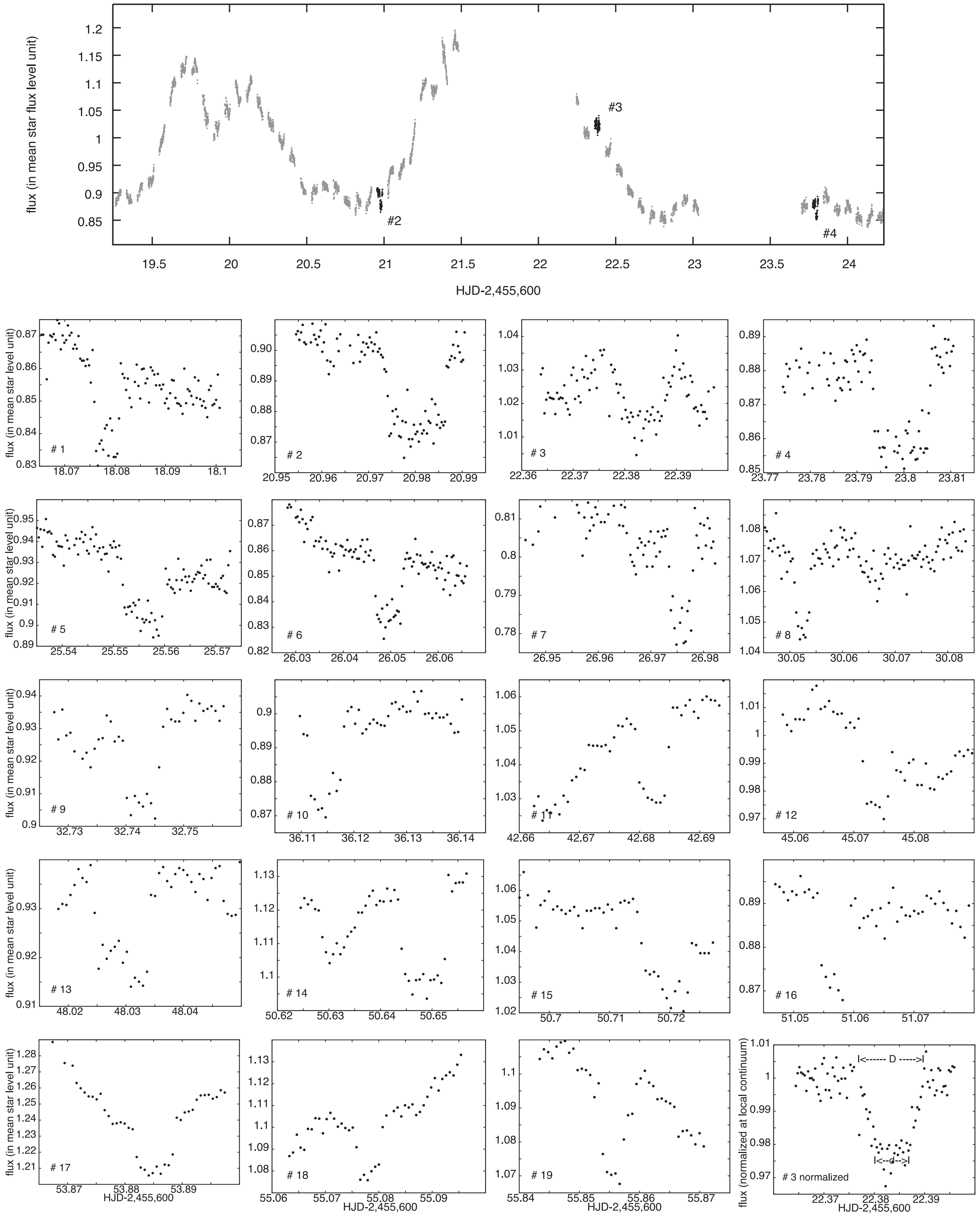

Figure 4. The fragment of the 2011 *MOST* light-curve (upper large panel) with occultations nos. 2, 3 and 4, shown in detail in the bottom panels along with all occultations detected by *MOST*. The numbers of occultations are given in the bottom left corner of each figure. The flux is left in normalized flux unit of the star mean brightness, as in Fig. 1. Occultations 1–8 were observed with 30-s integrations, and occultations 9–19 with 60-s integrations. The final small panel shows 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 (see Fig. 4): the central dip moments $hjd_{\min}$ = HJD − 2, 455, 600 are estimated from the mid-times of inner contacts, the dip depths are related to the continuum flux assumed as unity (see Section 4), the outer D and inner d contact durations are given in days (for a description see also the final panel in Fig. 4). The errors of the first two quantities are given in parentheses. Typical uncertainties of D and d are about 0.0003 d (0.5 min).

No.	$hjd_{\min}$ [d]	Depth [per cent]	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

them from the 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 occultations per day.

(3) Most of the events are flat-bottomed and look as though they were caused by total occultations.

(4) In order 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 relative to the local flux continuum normalized to unity are surprisingly similar and range between 1.87 and 3.03 per cent (see Table 1 and Fig. 5a).

(5) In Fig. 5(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, namely $(D - d)/2$ are very short, on average lasting for 0.00175 ± 0.0006 d (2.5 ± 0.9 min).

(6) We found four occultations (nos. 2, 3, 4, 13) lasting twice as long as 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 Fig. 5(c).

(7) We do not see any single occultation lasting less than 5 min, but this may be partly as a result of the spacing of observations of 1 min. Furthermore, owing to the specific format of *MOST* data (see Fig. 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.

(8) The regularity in the distribution of the occultations in time is difficult to characterize because of the breaks in the temporal coverage. We note, however, that the spacings between two pairs of occultations, nos. 8 and 9 (2.69015 d) as well as nos. 13 and 15 (2.69005 d), are identical within the measurement errors (∼0.0003 d, Table 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).

(9) The issue of the regularity of occurrence appears to be crucial in any attempt to discover the process producing the occultations. Even for a time series as uniform as our observations, however, there are unavoidable gaps in the coverage caused by the location of TW Hya outside 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 Fig. 5d). There exists a very well-defined primary broad peak, around 2.5 to 3.3 d, while the 5.75-d peak may be related to this feature for double spacing. Some secondary concentrations may be present at ∼1.5 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 in Fig. 5(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 the occultations been seen before and we simply overlooked them in our 2007, 2008 and 2009 *MOST* observations? The accuracy of the 2007 data was too low to allow for their detection. Although the 2008 and 2009 runs lasted 46.7 and 40.3 d, their effective strictly continuous time coverage was only 6.96 and 4.62 d, respectively. In this respect, the 2011 run, with the effective coverage of 16.92 d, was by far the most conducive for the 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 Fig. 6). Their depths are 1.0, 0.7 and 2.3 per cent, respectively, but only the last event is as well defined as any of the 2011 occultations. We infer that perhaps owing to different conditions producing the occultations, their shape, depth and occurrence rate can evolve from season to season.

Other T Tauri stars may also have shown occultations. Rapid brightness drops, but of very different depths and durations, were noted in the high-speed photometry of the CTTS DD Ser, Verlyuk (1995), for which much deeper, 0.3–0.7 mag, dips lasted for only 4–5 s. A single 1.2-mag, very brief (1.7-s) dip was also observed in AB Aur, a Herbig Ae star. For the latter star the inclination angle of the accretion disc is $29\overset{\circ}{.}8 \pm 1\overset{\circ}{.}3$ (Hashimoto et al. 2011), which is similar to that for the nearly pole-on disc in TW Hya.

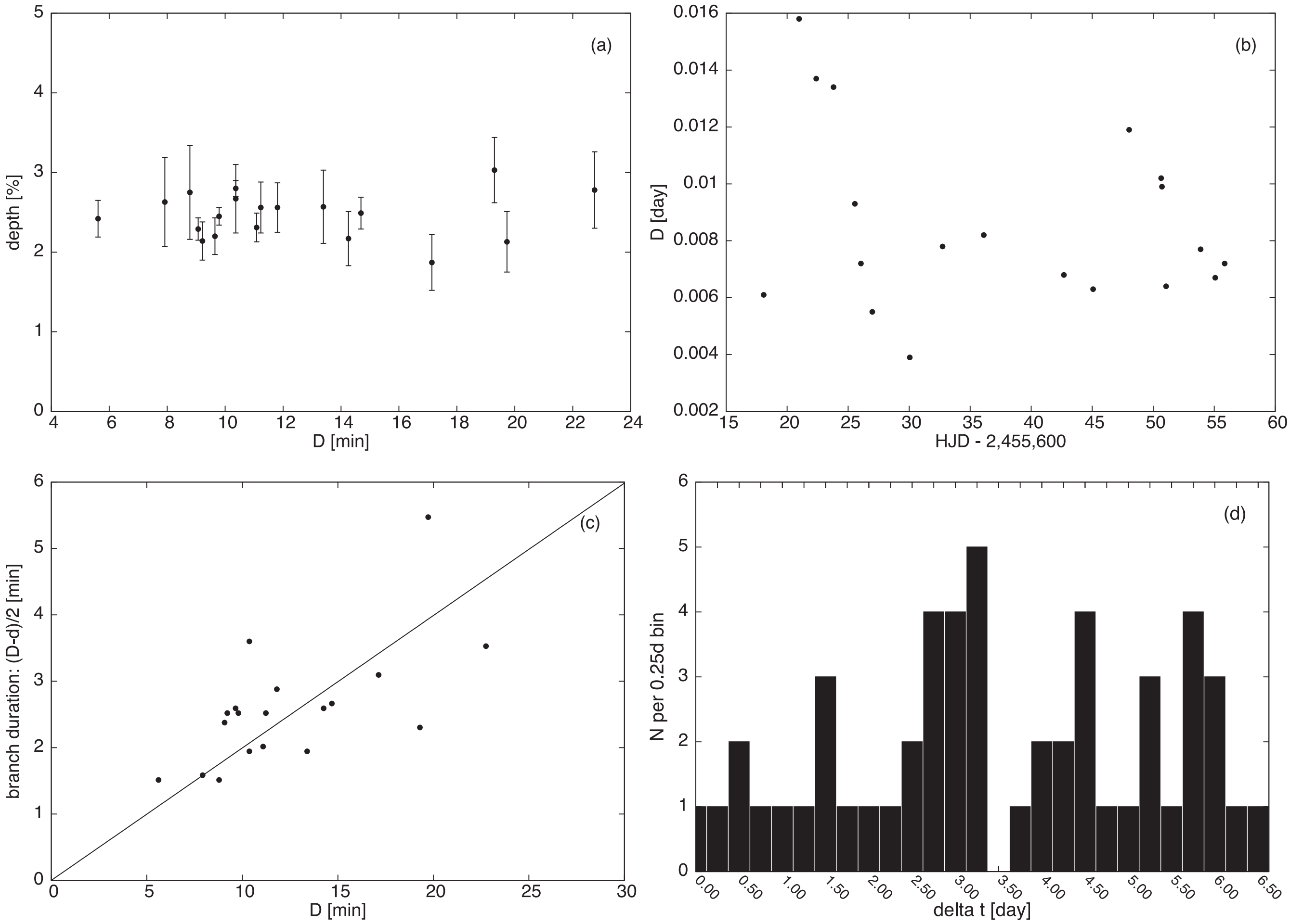

Figure 5. Relationships between various characteristics of the occultations: (a) relationship between the occultation durations D and their relative depths (in per cent); (b) distribution of the outer contact durations D in time; (c) relationship (a straight-line fit) between the durations D and the branch durations $(D-d)/2$: $(D-d)/2 = 0.199(14)D$; and (d) histogram of spacings between all available pairs of occultations.

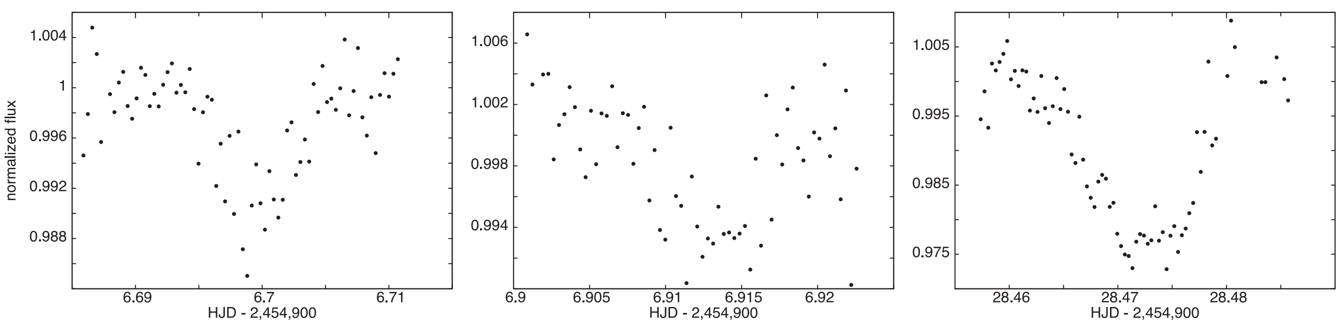

Figure 6. Possible occultations in the *MOST* 2009 light-curve of TW Hya, namely those obtained 2 yr before the discovery in observations reported here. Only the last two events fully meet the definition of an occultation as given in Section 4.1.

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), it would not be expected that planets would be observed 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 $i = 62^\circ \pm 4^\circ$.

Although the occultation depths of 2–3 per cent in Table 1 are similar to those caused by transits of giant planets, the short branch durations of about 2–3 min and the semiregular 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 caused by 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 did orbit the star on a polar orbit with a semimajor axis similar to the inner accretion disc radius of $12R_\odot$ (Eisner et al. 2006), the expected transit duration times for a 0.4–0.7 $M_\odot$ star (Vacca & Sandell 2011) would be about 2–3 h.

Through the process of elimination, we conclude that the occulted sources are probably hot regions of small, but finite, dimensions. These could be hotspots localized at the footprints of accretion tongues created through RT instabilities and/or sources of the numerous, strong emission lines observed in the 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), for the assumed 2.5 min of the branch duration and 3 d for their characteristic reappearance time indicated by the main broad peak in Fig. 5(d). Presumably, the inner disc and the stellar rotational frequencies comprise the most natural 'clocks' determining the temporal occurrence of the occultations.

We see no dependence between the eclipse depths and their durations (Fig. 5a), so that the eclipsed sources probably had very similar sizes and brightnesses during the entire 2011 *MOST* run. If these sources had additional freedom to move, as predicted for hotspots 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 (Fig. 5d) 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 a third one separated by 2.81 d, which consists of dips with very similar shapes and duration times (see Fig. 4 and 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 Fig. 5(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 the 'dusty traps' suggested on the basis of ALMA observations of Oph IRS-48 by van der Marel et al. (2013). They could also, however, be small optically thick plasma condensations (if not the accretion stream itself) levitating in the magnetic field of the steady accretion funnel encircling the stellar disc magnetosphere and acting as natural screens for the hotspots created at low or moderate latitudes of the star. This scenario could explain 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 were dominated by a single almost stable oscillation with a period of 4.18 ± 0.25 d. We propose that the dominant oscillation is caused by rotational modulation produced by a single, large hotspot formed close to the magnetic pole at the footprint of the accretion funnel that 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, namely numerous relatively short-duration (10–20 min), 2–3 per cent deep drops in brightness, which we term occultations. Their short branches, lasting typically about 2.5 min, indicate finite dimensions of the occulted source(s). Although without any temperature information we are unable to definitively interpret the observed phenomena, we suggest that they could be caused by the occultations of small hotspots on the star, created at moderate latitudes at the footprints of a few accretion tongues produced through the Rayleigh–Taylor instability. The obscuring bodies could be dark, free-floating condensed clumps orbiting the star on highly inclined orbits beyond the magnetosphere or optically thick plasma condensations levitating in magnetic fields within the accretion funnel. It is expected that multicolour and spectral, high-cadence observations of TW Hya will provide crucial information about the temperature of the occulted regions, which will in turn provide a firmer interpretation of our discovery.

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