Analysis of variability of TW Hya as observed by MOST and ASAS in 2009*

Michal Siwak,1† Slavek M. Rucinski,1 Jaymie M. Matthews,2 Grzegorz Pojmański,3 Rainer Kuschnig,2,4 David B. Guenther,5 Anthony F. J. Moffat,6 Dimitar Sasselov7 and Werner W. Weiss4

1Department of Astronomy and Astrophysics, University of Toronto, 50 St George Street, Toronto, Ontario M5S 3H4, Canada
2Department of Physics & Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, BC V6T 1Z1, Canada
3Astronomical Observatory, University of Warsaw, Al. Ujazdowskie 4, 00-478 Warsaw, Poland
4Institut für Astronomie, Universität Wien, Türkenschanzstrasse 17, A-1180 Wien, Austria
5Institute for Computational Astrophysics, Department of Astronomy and Physics, Saint Mary's University, Halifax, NS B3H 3C3, Canada
6Département de Physique and Centre de Recherche en Astrophysique du Québec, Université de Montréal, C.P. 6128, Succursale: Centre-Ville, Montréal, QC H3C 3J7, Canada
7Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

Accepted 2010 September 4. Received 2010 September 2; in original form 2010 August 1

ABSTRACT
As a continuation of our previous studies in 2007 and 2008, new photometric observations of the T Tauri star TW Hya obtained by the MOST satellite and the All Sky Automated Survey (ASAS) project over 40 d in 2009 with temporal resolution of 0.2 d are presented. A wavelet analysis of the combined MOST–ASAS data provides a rich picture of coherent, intermittent, variable-period oscillations, similarly as discovered in the 2008 data. The periods (1.3–10 d) and systematic period shortening on time-scales of weeks can be interpreted within the model of magnetorotationally controlled accretion processes in the inner accretion disc around the star. Within this model and depending on the assumed visibility of plasma parcels causing the oscillations, the observed shortest oscillation period may indicate the stellar rotation period of 1.3 or 2.6 d, synchronized with the disc at 4.5 or 7.1 R⊙, respectively.

Key words: accretion, accretion discs – stars: individual: TW Hya – stars: rotation.

1 INTRODUCTION
The data gathered by the MOST satellite in 2007 and 2008 for TW Hya – a T Tauri type star of spectral type K7Ve and V ∼ 11 mag surrounded by an accretion disc – were a subject of a Fourier and wavelet analysis by Rucinski et al. (2008). The most interesting discovery resulted from the wavelet analysis, which revealed oscillatory features systematically shortening their periods on time-scales of tenths of days. With typical periods of 2–9 d, a preliminary interpretation was through instability phenomena within the innermost accretion disc. In order to check whether such variations are a constant feature of the star, TW Hya was observed by the MOST satellite for the third (and most likely last) time in 2009 (Section 2).

Additionally, simultaneous All Sky Automated Survey (ASAS) observations were obtained as close to the MOST observation in time as possible. In this paper we present an analysis of the new photometric data (Section 3) and propose a more physical interpretation of the features discovered in the wavelet spectrum (Section 4).

2 OBSERVATIONS AND DATA REDUCTION
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 380–700 nm with effective wavelength falling close to Johnson’s 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).

TW Hya was observed between 2009 March 3 and April 12, corresponding to the hjd range of 4894.53–4934.83.1 The data were collected during the low stray-light segment, lasting typically 30 min, of almost every third satellite orbit over 40.3 d. The direct-imaging

*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, and from the All Sky Automated Survey (ASAS) (conducted by the Warsaw University Observatory, Poland) at the Las Campanas Observatory.
†E-mail: siwak@astro.utoronto.ca

1 Throughout this paper: hjd ≡ HJD – 245 0000.
The 2009 light curve of TW Hya in flux units, scaled (separately for each source) to unity at the mean brightness level. The original MOST data are presented as crosses and their respective median-orbital values are shown as black squares. The ASAS observations obtained at HJD = 4894.5–4903.9 in the Johnson V filter with 10 min temporal resolution, expressed in flux units assuming mean magnitude $\bar{V} = 11.065$, are shown as small dots; their mean values, calculated for intervals of 0.2114 d, corresponding to the MOST data collection rate of three satellite orbits, are shown as circles. Note the good match between the MOST and ASAS data sets where they overlap during the first 9 d of the MOST observations.

In parallel with the MOST observations, TW Hya was also monitored by the ASAS (Pojmanski 1997) in Johnson V filter with temporal sampling of about 10 min. Due to deterioration of the CCD chip used for V-band observations over the last years, the individual data points have rather low accuracy with a median error of 0.045 mag. The mean observed magnitude, $\bar{V} = 11.065$, was used for conversion of the ASAS data to normalized flux units. Similarly as in 2008 (Rucinski et al. 2008), the 2009 data show good correspondence between MOST and the ASAS V-band. For comparison with the MOST observations, the ASAS V-band data points were averaged using the sampling rate of the MOST data of 0.21142 d.

In Fig. 1 we present the original and the averaged data points of TW Hya obtained by the MOST satellite and ASAS in Johnson V filter in normalized flux units. The median error of the time-averaged MOST data in flux units is equal to 0.0066. The time-averaged ASAS V-band data have an order of magnitude worse accuracy of about 0.041 flux units. For both data sets, the errors include the genuine, time-averaged, short-time-scale physical variability of TW Hya observed within individual MOST orbits; thus, the rapid variability of the star was lost in the averaging process, similarly as in the previous analysis of the 2007 and 2008 data (Rucinski et al. 2008).

3 ANALYSIS OF MOST 2009 DATA

3.1 Fourier transform

We performed a Fourier analysis of the 2009 data as in Rucinski et al. (2008) (see section 4.2 of that paper for details). The frequency spectrum was obtained using the light curve formed from the averaged MOST and ASAS V-band data, represented by squares and circles, respectively, in Fig. 1. The 0.2114-d sampling rate (3 $\times$ the MOST orbit duration) precludes analysis of frequencies higher than 2.35 cycle d$^{-1}$. In Fig. 2, we show only the frequency range below 1 cycle d$^{-1}$ because there are no statistically significant peaks at higher frequencies. We note that Günther et al. (2010) did not find any subminute periodicities in their high-speed time-series data.
photometry of TW Hya obtained with the Southern African Large Telescope (SALT).

Because the temporal resolution of the 2009 data was three times poorer than that of the 2008 data, the amplitude errors are now larger than before, with median value of the error 0.012 of the mean flux. As observed before, the peak amplitudes \( a(f) \) seem to scale as flickering noise \( a(f) \sim 1/\sqrt{f} \), but due to the larger errors, this tendency is not as obvious as in the 2008 data (Rucinski et al. 2008).

### 3.2 Wavelet analysis

The original time distribution of averaged data points differs slightly from the uniformity required by the wavelet technique. Therefore, we interpolated the data into a uniform time grid using splines. Except for the orbital-averaged MOST data points, we also included the first five average ASAS points obtained in \( V \) band before and during the gap in the MOST data which occurred within \( \text{hjd} \approx 4895-4896.5 \). The remaining ASAS points were not used because the ASAS data were significantly less accurate and were used here only to assure uniformity of the main MOST sequence for the wavelet analysis.

Fig. 3 shows the result of the wavelet transform of 191 data points uniformly distributed in time at the spacing of 0.2114 d. As in the case of the 2008 data, the Morlet-6 wavelet provided the best match between the time-integrated power spectrum and original frequency spectrum, as is visible in the right-hand panel of Fig. 3. We stress that only for the Morlet-6 wavelet do we obtain such a nearly perfect match of both plots; as described in Rucinski et al. (2008) Morlet transforms of other orders result in systematic differences in the period scale.

### 4 DISCUSSION

The most important result of this study is that the general behaviour of the Morlet wavelet transform in the time–period plane is similar to that obtained and described by Rucinski et al. (2008) for the 2008 observing season. The systematically migrating oscillatory features that we saw in 2008 were not an unusual phenomenon limited to this particular point in time; apparently, TW Hya shows this phenomenon all or most of the time. The new 2009 data not only confirm the direct visibility of the features drifting to shorter periods, but this time we could identify as many as four of them. Their approximate moments of appearance and disappearance (in \( \text{hjd} \)), the periods \( P \) observed at the beginning and at the end of each oscillation packet and the respective Keplerian radii \( a_1 \) calculated assuming \( M_*=0.72 \, M_\odot \) and \( R_*=1 \, R_\odot \) are presented in Table 1; they are ordered in their start periods. The data in Table 1 for features 1–3 were obtained by tracing local maxima along the patterns in Fig. 3; similarly we used fig. 8 of Rucinski et al. (2008) to trace feature 5* identified in the 2008 data. We did not investigate features 4 and 6*: the former had a long period of almost 10 d, so that the 2009 run was too short to fully follow its evolution while the latter feature (from the 2008 data) occurred too close to the end of that observing run.

Within the accuracy of locating the local peaks, only the lowest order fits by straight lines (see Fig. 4) gave a sufficiently significant description of their temporal evolution described by their time derivatives \( \dot{P} \), as given in Table 1. The fits were weighted by their local peak intensities. We note that the rate of the period change appears to be faster for longer periods.

In the most popular interpretation now, originally developed for accreting neutron stars by Ghosh, Lamb & Pethick (1977) and Ghosh & Lamb (1979a,b) and further applied to classical T Tau
Table 1. Numerical values extracted from the wavelet spectrum and related physical parameters computed assuming that the features observed in the spectrum come from a Keplerian disc around the central star. The features marked with an asterisk (*) are for the data in Rucinski et al. (2008).

<table>
<thead>
<tr>
<th>Feature</th>
<th>hjd</th>
<th>P (d)</th>
<th>P</th>
<th>a₁(Rʘ)</th>
<th>a₂(Rʘ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – start</td>
<td>4901</td>
<td>1.9</td>
<td>0.049(2)</td>
<td>5.8</td>
<td>9.2</td>
</tr>
<tr>
<td>1 – end</td>
<td>4913</td>
<td>1.3</td>
<td>0.065(1)</td>
<td>4.5</td>
<td>7.1</td>
</tr>
<tr>
<td>2 – start</td>
<td>4898</td>
<td>3.1</td>
<td>0.151(3)</td>
<td>8.0</td>
<td>12.7</td>
</tr>
<tr>
<td>2 – end</td>
<td>4922</td>
<td>1.6</td>
<td>0.151(3)</td>
<td>5.2</td>
<td>8.2</td>
</tr>
<tr>
<td>3 – start</td>
<td>4902</td>
<td>7.2</td>
<td>0.151(3)</td>
<td>14.1</td>
<td>22.3</td>
</tr>
<tr>
<td>3 – end</td>
<td>4931</td>
<td>3.0</td>
<td>0.151(3)</td>
<td>7.8</td>
<td>12.5</td>
</tr>
<tr>
<td>4 – start</td>
<td>4914</td>
<td>9.8</td>
<td>0.151(3)</td>
<td>17.3</td>
<td>27.4</td>
</tr>
<tr>
<td>5* – start</td>
<td>4533</td>
<td>6.0</td>
<td>0.151(3)</td>
<td>12.5</td>
<td>19.8</td>
</tr>
<tr>
<td>5* – end</td>
<td>4553</td>
<td>3.0</td>
<td>0.151(3)</td>
<td>7.8</td>
<td>12.5</td>
</tr>
<tr>
<td>6* – start</td>
<td>4556</td>
<td>7.5</td>
<td>0.151(3)</td>
<td>14.5</td>
<td>22.9</td>
</tr>
</tbody>
</table>

Figure 4. The linear fits (thick black lines) to the local maxima of features 1–3 visible in Fig. 3. Similar fits were made for the features observed in 2008 of which only feature 5* could provide sufficiently well-defined results.
accretion and seem to be slow rotators. We note that the small value of $v \sin i = 10.6 \, \text{km s}^{-1}$ determined by the authors for TW Hya should not be taken to indicate a long rotational period of the star, but is rather a result of the low inclination angle of its rotation axis (Wilner et al. 2000).

Because of the pole-on geometry of TW Hya, Alencar & Batalha (2002) conclude that it is rather unlikely that the observed light variations are caused by rotation of hotspots on the star photosphere, especially in the case when magnetic poles seem to be aligned with the stellar rotation axis (see section 4 of their paper for a detailed explanation). These considerations may also apply to the theoretical prediction of regularities in the geometrical spot distribution as well as quasi-periodic light oscillations caused by hotspots on the stellar photosphere (Kulkarni & Romanova 2009; Romanova & Kulkarni 2009). Although the oscillations may have similar characteristics to light variations observed by MOST, a long rotational period of TW Hya (of the order of 10 d) would be required to be explained by such a mechanism. We note that neither the 2008 nor the 2009 MOST observations revealed any common long-period (8–15 d) features, such as aliased periods. These observations are consistent with Keplerian motion of optically thick plasma condensations in the inner accretion disc. The observed periods are consistent with the inner accretion disc, several stellar radii outside of the corotation and truncation radii. Noting the pole-on geometry of the accretion disc for TW Hya, consideration should be given to the possibility that the observed periods represent the respective halves of the true orbital periods. Assuming that we detected the shortest possible period in the Morlet wavelet transform of 1.3 d and that the inner boundary of the disc corotates with the star, the corotation radius for TW Hya would be about 4.5 ± 0.2 or 7.1 ± 0.4 $R_\odot$ depending on the assumed period (1.3 ± 0.1 or 2.6 ± 0.2 d, respectively); for the longer period the inner disc size is in accordance with the results of Weinberger et al. (2002) and Eisner et al. (2006), obtained from spatially resolved infrared images and interferometric observations. Determination of the rotational period of the star is crucially important both for the inner accretion disc considerations as well as for mechanisms investigated theoretically by Kulkarni & Romanova (2009) and Romanova & Kulkarni (2009) which could explain light variations through (possibly time-evolving) geometrical distribution of hotspots and/or quasi-periodic oscillations in this region.

**ACKNOWLEDGMENTS**

MS acknowledges the Canadian Space Agency Post-Doctoral position grant to SMR within the framework of the Space Science Enhancement Programme and thanks Professor Ray Jayawardhana for advice and comments.

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 Space Agency and the Austrian Science Fund.

Special thanks are due to the referee, Dr W. Herbst, for very useful comments and suggestions.

**REFERENCES**

Pojmanski G., Acta Astron., 1997, 47, 467

This paper has been typeset from a TeX/LaTeX file prepared by the author.