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WAVELET ANALYSIS OF TAURUS K2 DIPPER LIGHT CURVES

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Abstract. During the evolution of T Tauri stars and the formation of their planetary systems, accretion processes play a key role. However, the more complex interaction at the rim of the inner region of the disk is still not fully understood. The SPIDI (Star-Planet-Inner Disk-Interactions) project aims to further investigate this phenomenon and its influence on forming planets in the inner disk.

The magnetic field of a young star truncates the disk where the magnetic field pressure is equal to the ram pressure of the accreting material. Thus, the dust and the gas present in the disk are lifted above the plane along the magnetic field lines. If the temperature is low enough for dust to survive, this accretion warp obscures the star and causes eclipses observable with photometry, i.e. the dipper phenomenon. The periodicity of a dipper star depends on the stability of the dusty warp.

In this work, wavelet analysis of the K2 light curves from the Taurus region allows us to study the time-resolved periodicity of the dippers and other signals present in the light curves. This information, together with further fitting with an occultation model, dust survival models, and radiative transfer modelling, will allow us to isolate a possible planetary signal embedded in accretion-driven photometric variability.

Keywords: stars: variables: T Tauri, protoplanetary disks, techniques: photometric

1 Introduction

Classical T Tauri stars (CTTSs) are low-mass, pre-main sequence stars which are still accreting from their circumstellar disks. They are Class II protostars, which means that the main contribution to the SED is given by stellar radiation, while a significant infrared excess from the disk is present.
The disk itself might extend up to hundreds AU. We will focus on the very inner part of the disk –at a scale of a few stellar radii, i.e. $\sim 0.02\,\mathrm{AU}$–, where dust evaporates and the accretion takes place onto the star. This region is very challenging to observe, as it is at the limit of the resolution of interferometry. Light curves allow an indirect observation of the phenomena occurring at the inner disk rim.
In recent years, it was noticed that a significant percentage of T Tauri stars –around 30% of the disk-bearing stars– display eclipses in their light curves that cannot be traced back to binarity. It was supposed that these "dipper" light curves are caused by dusty material from the disk, that occults the star during its rotation (e.g., Cody et al. (2014), Alencar et al. (2010)).
The occurrence of dippers might be explained by the magnetospheric accretion model (Bouvier et al. 1999). The inner disk is truncated when it reaches the magnetosphere of the star, as its material is accreted onto the star following the magnetic field lines. If the temperature in this region is cool enough for dust to survive, dust might be lifted above the disk plane in form of an accretion stream or warp. An observer at a high inclination angle will thus be able to observe a dipper light curve (Bodman et al. 2017).
Photometric observations can thus deliver information about the position and the temperature at the truncation radius, which is of vital importance for understanding the interaction between the star and the inner disk.

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2 Observations and Data Reduction

The Taurus region was observed nearly continuously with the *Kepler* satellite within the framework of the K2 mission, with a cadence of 29.4 min and a duration of 80 days. The observation campaigns C13 (Mar - May 2017) and C4 (Feb - Apr 2015) delivered light curves for about 900 potential members.
K2 data are challenging to reduce and several pipelines are available for this purpose. If the light curve does not present particular issues, we used the version with moving aperture as in Cody & Hillenbrand (2018) as default and performed a more careful inspection on dipper candidates.
The process to assess the membership of each star to the cluster is explained by Rebull et al. (in prep.). We attribute higher confidence membership to candidates which already appear as members in Luhman (2018). Finally, we produce a sample of 225 Taurus members with K2 light curves and use it as basis to search for dippers.

3 Wavelet analysis of dippers

Detailed information on the periodicity of dippers is necessary to derive a number of parameters, among them the location of the dusty warp that obscures the star.
The exact configuration of the inner disk changes from cycle to cycle; dippers are thus either aperiodic or quasi-periodic phenomena. This distinction is important, as aperiodic dippers seem to be generated by different mechanisms than quasi-periodic ones (Ansdell et al. 2016; Stauffer et al. 2015). In some cases, the occultations are transient, making it difficult for classic period-finding algorithms to determine the correct period. It is also interesting to find out if the period evolves over time.
The wavelet transform is an efficient tool to analyze the frequency spectrum of a signal and to gain time resolution (see Torrence & Compo (1998)). Lately, the tool has found application in light curve analysis (e.g., Hedges et al. (2018), Bravo et al. (2014) and García et al. (2014) for *Kepler* light curves).
It can be viewed as a time-resolved Windowed Fourier Transform (WFT) with variable window width, that reveals both high and low frequency features. The wavelet, which is a finite wave in the time domain –instead of an infinite sinusoid as in the Fourier transform– is convolved with the signal at each position with a given time step. To gain time resolution, the wavelet is scaled in the time domain (i.e. stretched or compressed) and again convolved and shifted along the signal. A high correlation between the wavelet and the time series results in high power in the Wavelet Power Spectrum (WPS).
In this work, the complex Morlet wavelet is used, as it is a good compromise between time and frequency resolution and allows for adjustment of these two parameters according to one's needs.

4 Results

The dippers are identified among the Taurus members from a visual inspection of the light curve. We classified by eye 35 young stars as either dippers or variable stars that show dips in their light curves as secondary variability. Among the 23 stars classified as dippers, 12 are periodic and the rest are either aperiodic or show complex periodicities. The period range varies between 2 and 11 days and most of the stars have a period shorter than 5 d.
An example of a periodic dipper (JH 223) is shown in Fig. 1. The star displays a constant brightness and periodic dips, which vary in shape and depth. The Wavelet Power Spectrum (WPS) shows the power at different periods (y-axis) at different positions in time (x-axis). The comparison with the CLEAN periodogram (Roberts et al. 1987) illustrates the loss of frequency resolution in the wavelet transform. The exact values of the period are, where possible, retrieved from the periodogram.

GH Tau is a good example where wavelet analysis is beneficial to interpret a complex periodogram (Fig. 2, left panel). By looking at the WPS, it becomes clear that most of the peaks seen on the periodogram are local periodicities, while only the two highest peaks might be real periods. At the same time, the double peak illustrates well the uncertainty principle of time and frequency resolution, since it is not resolved on the WPS.

JH 112 is a transient, periodic dipper. The mostly constant brightness makes it difficult for the periodogram analysis to reach a high detection significance (Fig. 2, right panel). The WPS shows how the local periodicity

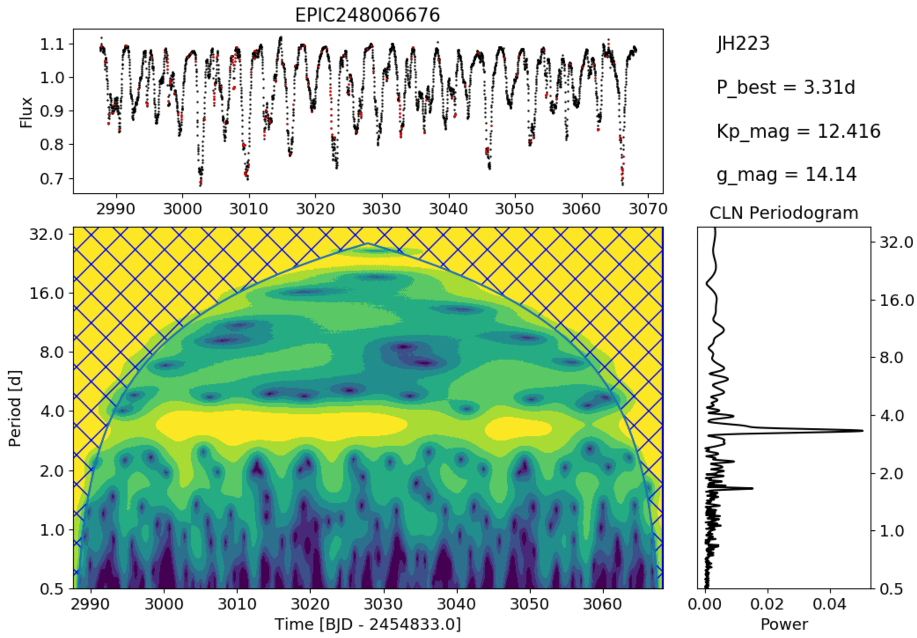

Fig. 1. In order to perform the wavelet transform, the K2 light curve (top) is linearly interpolated at the missing values (red dots). The Wavelet Power Spectrum shows the time-resolved frequency spectrum (bottom). The contours indicate the power of a certain period at a certain point in time; yellow contours have the highest power, blue ones the lowest. In order to obtain a better contrast, the contours are saturated at the 3 and 99 percentile. The Cone of Influence (crosses) delimits the area where the WPS is affected by edge effects; a high power in this region is not significant. The WPS is compared to a CLEAN periodogram (right).

corresponds to the visually detectable dipping.

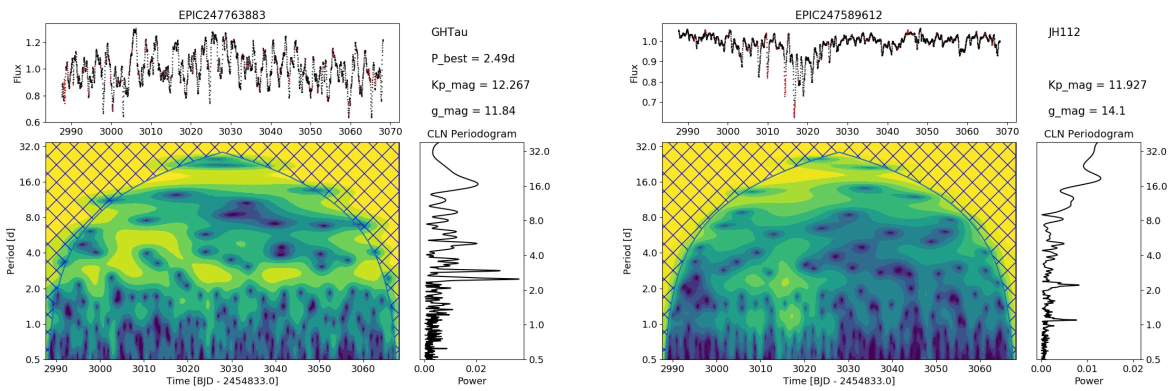

Fig. 2. Left: Light curve, periodogram and WPS of GH Tau. **Right:** Light curve, periodogram and WPS of JH 112.

5 Conclusions and Outlook

The application of wavelet analysis to dipper light curves allows us to more thoroughly study their periodicity. Among the 225 Taurus members, 35 show dipping events in their light curves. Of the 23 dippers with no other evident variability, about 50% are periodic with periods between 2 and 11 d. This information allows us to compute the location of the dusty warp. Furthermore, a simple occultation model makes it possible to derive the geometry of the system, i.e. the inclination, the warp's maximum height and its azimuthal extension. In upcoming work, a full modeling will be attempted using the MCFOST radiative transfer code (Pinte et al. 2006), to hopefully reach beyond the simple detection of the main periodicity.

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