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THE DIPPER STAR POPULATION OF TAURUS SEEN WITH K2

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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 well understood. Some young stars exhibit recurrent, quite irregular flux dips in their photometry (dippers). These can be explained as extinction events by dusty material from the protoplanetary disk, which is finally accreted onto the star. In the magnetospheric accretion scenario, 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. If the temperature close to this distance is low enough to avoid dust sublimation, dust might be lifted above the disk plane and obscure the star. The dataset for this study consists of K2 light curves (C4 and C13) of the Taurus region, which was observed continuously for ∼80 days. The stars classified as dippers have spectral types K4-M6, consistent with studies in other regions, and the mass range goes down to the brown dwarf limit. The co-rotation radii can be derived to a few stellar radii, with temperatures at corotation < 1600 K, that indicates that in most cases dust could survive at corotation. Temperatures close to 1600 K give some constraints about the dust composition. Magnetospheric accretion can account for most of the light curves. However, for some dippers, also other phenomena might cause eclipses.

Keywords: protoplanetary disks, stars: pre-main sequence, stars: variables: T Tauri, accretion, accretion disks, techniques: photometric

1 Introduction

Classical T Tauri stars (CTTSs) are low-mass, pre-main-sequence stars. They are $\sim 10^6$ Myr old and are surrounded by a protoplanetary disk, from which they accrete gas and dust in its inner region. The star-disk interaction is regulated by the stellar magnetic field, which truncates the disk at distances < 0.1 AU and drives accretion along the magnetic field lines. CTTSs display a strong variability in both their spectra and their light curves. Many physical mechanisms have been proposed to explain this variability, such as accretion hotspots, accretion bursts, or occultations by dusty structures in the disk (e.g., Cody et al. 2014; Alencar et al. 2010; Bouvier et al. 2003). This talk focuses on a class of variable stars that show dips in their light curve, the so-called 'dippers' . The dips present an irregular shape and can be quasiperiodic or aperiodic. They are mostly of late spectral type (K to M) and seem to be fairly common among CTTSs, with occurrences of 20% to 40% of young stars. AA Tau was the first dipper studied in detail. Bouvier et al. (1999, 2007) proposed that the magnetic field lines, close to the truncation radius, could lift dust above the disk midplane, and that an observer would see dips in the light curve whenever the dust crossed the line of sight. The temperature in this region must be low enough for the dust to survive at this distance, and the inclination of the system sufficiently high for the observer to look through the dusty structure (Bodman et al. 2017). Photometric observations can thus help to better understand the accretion processes and the inner disk structure on scales that are still challenging to resolve directly with interferometry.

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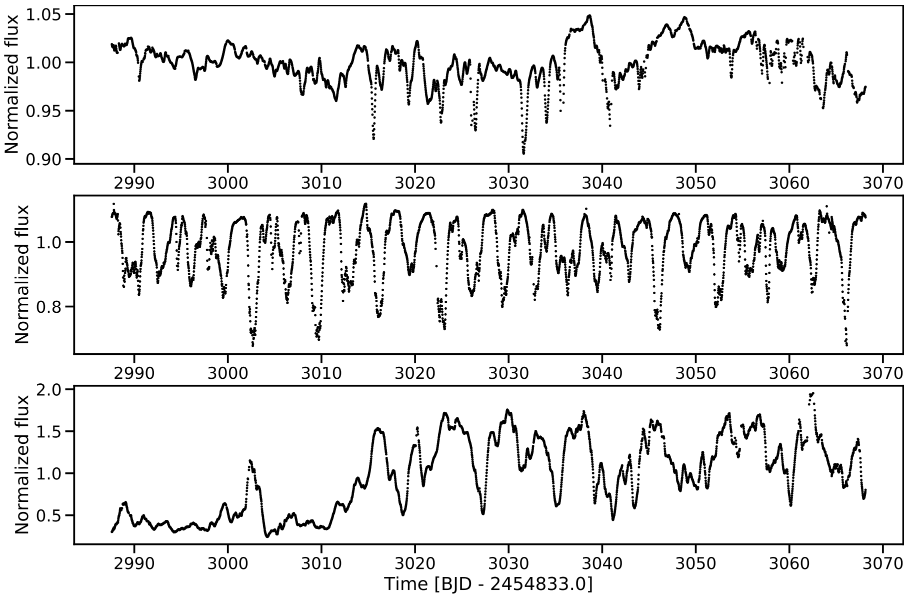

Fig. 1. Examples of an aperiodic dipper (HD 285893, top) a quasiperiodic dipper (JH223, center), and a dipper with a rather complex light curve (DK Tau, bottom).

2 Observations and data reduction

The Taurus region was observed nearly continuously with the Kepler satellite within the framework of the K2 mission (Howell et al. 2014), 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. We compared different reduction pipelines and if the light curve did not present particular issues, we used the version with moving aperture as in Cody & Hillenbrand (2018) as default for consistency. The process to assess the membership of each star to the cluster is explained by Rebull et al. (2020). We attribute a higher-confidence membership to candidates which already appear as members in Luhman (2018). Finally, we searched for dippers in a sample of 156 members plus 23 possible members of Taurus.

3 Results

From the sample of members and possible members of Taurus, we identified 22 dippers, which are studied in more detail, and 12 additional dippers, which are dominated by another type of variability and display mostly aperiodic dips in their light curve (Roggero et al. 2021). This sums up to an occurrence of 20% among Taurus members, and of 30% among disked stars in the sample. This has to be considered as a lower limit to their true occurrence, due to both the observational limits (e.g., the system geometry) and the ephemerality of dippers. A majority of CTTSs might be a dipper at some point of its evolution.

Several properties of dippers are useful to gain information on the inner disk region and the star itself. All possible explanations for dippers converge on a dusty structure at the origin of the dips in the light curve. Thus, dip amplitude and dip width should provide hints on the geometry of this structure. At the same time, several other parameters allow to probe the different models. The hypothesis that the material provoking the occultation is corotating with the star can be probed by studying the dippers' periodicity, and comparing it to the stellar period. The temperature at the corotation radius should be below the dust sublimation temperature ($1500 - 1600\,\mathrm{K}$) and the viewing angle of the system can exclude certain dipper models.

3.1 Periodicities

For the aim of studying the periodicities of dippers, we used different algorithms: Lomb-Scargle periodogram (Rebull et al. 2020), CLEAN periodogram and wavelet analysis (Roggero et al. 2021). The latter method opens the possibility of time-resolved frequency analysis. Considering both the dipper sample studied in more detail and the dippers dominated by another variability (mostly cold stellar spots), the ratio of periodic to aperiodic dippers is of $\sim 1 : 1$. The periods are in the range of a few days, in accordance with the rotation periods of CTTSs, supporting the hypothesis of dust at corotation. In the case of the presence of both spots and dips in the light curve, the periods are slightly, yet not significantly different.

3.2 Dips' morphology

We identify dippers based on their light-curve morphology. This type of light curves presents irregularly shaped, sharp dips which can be aperiodic or quasiperiodic in their occurrence (Fig. 1). In order to study the dip morphology, we defined the dip amplitude as difference between the 90th and fifth percentile of flux of the detrended light curve. The amplitude of the dips can be influenced by, for example, the viewing angle, the height and the optical thickness of the dusty structure. We also defined a dip width as full width of half maximum of the detrended, phase-folded and then binned (that is, averaged) light curve (for more details, see Roggero et al. 2021). The dip width is a measure of the azimuthal extension of the occulting feature. We investigated whether dip width and dip amplitude correlate, as it might be expected following the model of the dusty disk warp (Bouvier et al. 1999), but we could not determine any correlation. However, we found a correlation between the dip width in units of phase and the dips' period, which was not found before (Roggero et al. 2021). It appears that the dip width increases with the period. This would imply that slow rotators are surrounded by azimuthally larger dusty warps. We speculate that large-scale magnetic fields might be at the origin of this correlation, by having a stabilizing effect on large warps.

3.3 Stellar parameters

We derived stellar luminosities by using photometric data from the literature, and effective temperatures by means of the conversion tables of Pecaut & Mamajek (2013). The resulting Hertzsprung-Russel diagram is shown in Fig. 2. We used the evolutionary models of Baraffe et al. (2015), as they include the lowest stellar masses. Almost all dippers of the sample have masses $< 1\,\mathrm{M}_\odot$, with the lowest ones close to the brown-dwarf limit. Despite the large uncertainties on their age, the stars are spread around the 1 Myr isochrone. These parameters can be used to derive the extent of the corotation radius as in:

$$R_{\rm cor} = \frac{P}{2\pi}^{\frac{2}{3}} (GM_*)^{\frac{1}{3}}. \tag{3.1}$$

The corotation radii are located at a few stellar radii, as expected for dippers. We can verify whether dust can survive at this distance from the star with the following approximation:

$$T_{\rm cor} = 2^{-\frac{1}{2}} T_{\rm eff} \left(\frac{R_*}{R_{\rm cor}}\right)^{\frac{1}{2}}. \tag{3.2}$$

For all dippers, the temperatures at corotation are below 1600 K, which is considered as an upper limit for dust sublimation. We also derived stellar inclinations following:

$$v \sin i = \sin i \frac{2\pi R_*}{P}. \tag{3.3}$$

This parameter is crucial to probe the different models proposed for dippers, as they depend on the viewing angle of the system. In fact, the dusty material has to cross the observer's line of sight in order to produce dips in the light curve; at the same time, dust is not supposed to be present close to the stellar poles. The inner disk wall first proposed by Bouvier et al. (1999) for AA Tau requires high inclinations $\sim 70°$, while the generalization of the magnetospheric accretion model (Bodman et al. 2017) can account, under certain conditions, for inclinations down to $\sim 50°$. Dusty disk winds, which have been invoked to explain dippers at low inclination, seem to be observable at rather high inclinations close to $\sim 70°$ (Vinković & Čemeljić 2020). The dippers of this sample are seen under moderate to high inclination, thus compatible with the generalized magnetospheric accretion model, but with few exceptions. We also retrieved inclinations of the outer disk from the literature, as observed at mm wavelengths. In general, the star has a higher inclination than the outer disk. This might be due, on one hand, to the high uncertainty on $\sin i$, which grows with the inclination. On the other hand, recent observations point out that misalignments between inner and outer disk might be pretty common among CTTSs.

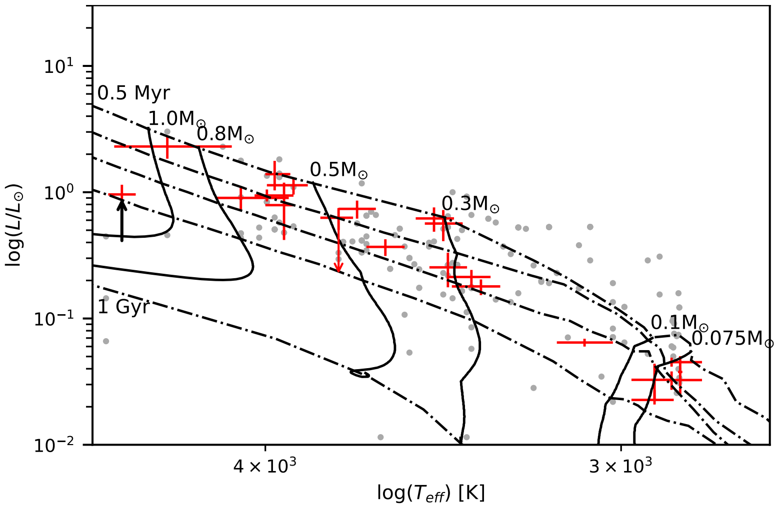

Fig. 2. Hertzsprung-Russell diagram of the studied sample of 22 dippers. The evolutionary tracks (solid lines) and the isochrones (dashed lines) are from Baraffe et al. (2015). Isochrones from top to bottom: 0.5, 1, 2, 5 Myr, and 1Gyr. The grey points represent other stars in Taurus as in Herczeg & Hillenbrand (2014). For the seek of readability, HD 285893 (spectral type F8) does not appear on this plot. All dippers are scattered around ~ 1 Myr and are fully convective, with the exception of LkCa 15 (indicated with an arrow).

4 Conclusions

We have searched for dippers in a sample of 156 + 23 Taurus members and found 22 dippers, with 12 additional dippers which display a different predominant variability. As a result, around 20% of Taurus members and 30% of disk-bearing stars in Taurus are dippers, as found also in surveys of other star-forming regions. This occurrence is a lower limit, due to the ephemerality of dippers and the observational constrains. The stars analyzed in this study are compatible with the presence of dust at corotation and magnetospheric accretion can account for most, but not all, dipper light curves. Future studies on this dipper sample will consider in more detail the cycle-to-cycle variation of the dips, which might provide a more complete picture of accretion and dust depletion on short time scales.

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