A study of classical T Tauri stars in NGC 2264 with extinction dominated light curves*

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1 Introduction

Young star-disk systems observed at a high inclination relative to their rotation axis often show photometric variability caused by extinction events due to circumstellar material eclipsing the stellar photosphere. In many cases, short periods associated with this variability indicate that the occulting material is located in the innermost region of the accretion disk (few 0.1 AU from the stellar surface), where the disk interacts strongly with the stellar magnetosphere and accretion columns are formed. In this way, these systems represent an opportunity to study the interaction between magnetosphere and disk through indirect measurements, in a region where direct imaging is not yet possible. By analysing these systems simultaneously in a range of different wavelengths using different techniques, we can attempt to better understand the processes that occur in this region.

1.1 AA Tau

During a study conducted in 1995, the classical T Tauri star (CTTS) AA Tauri presented photometric variability that was attributed to occultations by an inner disk warp, proposed to be caused by the interaction between the inner disk and an inclined magnetosphere (Bouvier et al., 1999). Its light curve showed a relatively stable maximum brightness level interrupted by quasi-periodic dips of around 1.4 magnitudes. A simple geometrical model was proposed to explain these dips, in which an optically thick clump of given maximum height h_{max} and azimuthal extension ϕ_w, present at the co-rotation radius R_{co}, periodically occults the stellar photosphere of a system seen at inclination i as the system rotates (Fig. 1).

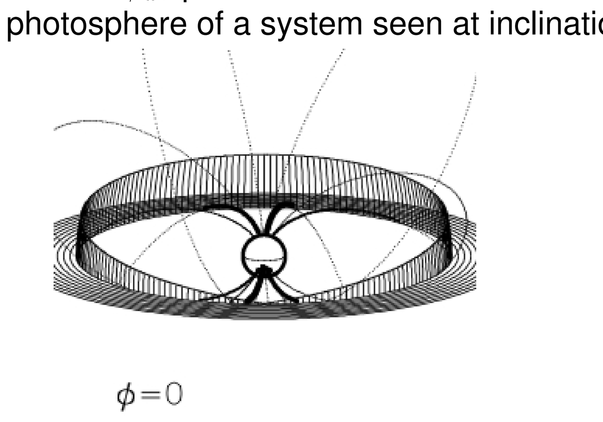

Figure 1. A clump of given maximum height h_{max} and azimuthal extension ϕ_w, present at the co-rotation radius R_{co}, periodically occults the stellar photosphere of a system seen at inclination i. Figure from Bouvier et al. (1999)

2 Observations in NGC 2264

NGC 2264 is a young open cluster in the Monoceros constellation, containing hundreds of young stellar objects (YSOs). Between December 2011 and March 2012 it was the object of an observational campaign entitled the "Coordinated Synoptic Investigation of NGC 2264" (CSI2264, Cody et al., 2014), which was composed of simultaneous spectroscopic and multi-band photometric observations using 11 ground-based telescopes and 4 space-based telescopes, including CoRoT and *Spitzer*. The CoRoT satellite, which had already observed the cluster for 28 days uninterruptedly in March 2008, observed it again for 40 days, along with 30 days of *Spitzer* observations. The FLAMES multi-object spectrograph on the VLT obtained 20-22 high- and medium-resolution spectra of 58 cluster members classified as CTTSs, up to 6 of which occurred simultaneously with CoRoT. NGC 2264 was also observed for 14 days in February 2012 in the u and r bands with the CFHT MegaCam, and for nearly 4 months in the I band with the USNO 40" telescope. This campaign provided us with simultaneous photometric and spectroscopic information in a wide range of wavelengths for hundreds of YSOs.

During both CoRoT observing runs, many CTTSs with light curves resembling that of AA Tau's 1995 light curve were found (Fig. 2). We call them AA Tau-like light curves and attribute their behavior to periodical occultations of the photosphere by circumstellar matter, possibly distributed in an inner disk warp, as was proposed for AA Tau. Of the 159 CTTSs observed by CoRoT in 2008 and/or 2011, 23 showed this behavior in one epoch or both. Another 10 stars presented similar photometric behavior, but were not periodic in either observing run. We attribute their behavior to occultations of the photosphere by material randomly lifted above the disk midplane because of instabilities in the disk.

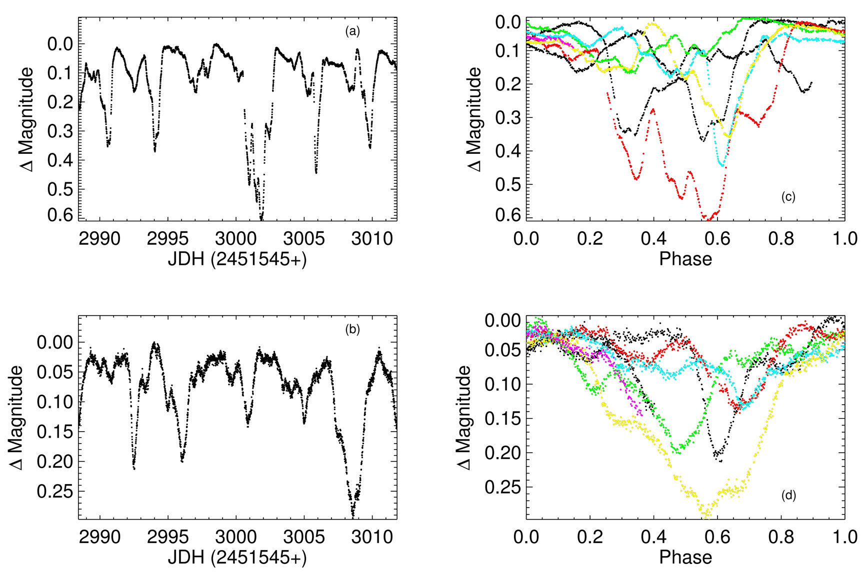

Figure 2. Left: AA Tau-like CoRoT light curves found in NGC 2264 by Alencar et al. (2010). Right: the same light curves folded in phase. Different colors represent different rotation cycles.

3 Analysis and Results

3.1 Periodic and aperiodic photometric behavior

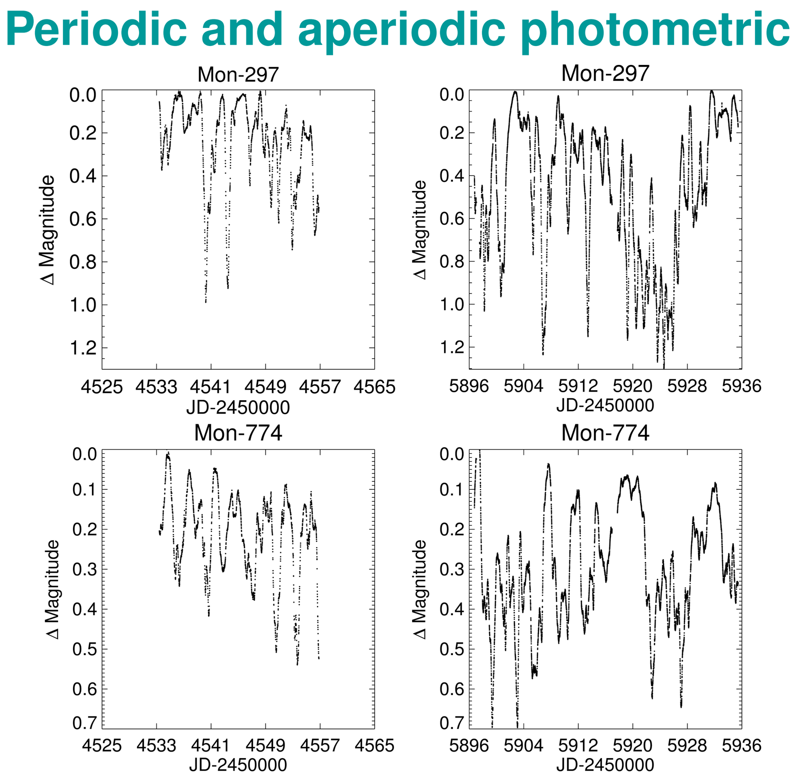

Figure 3. Corot light curves of Mon-297 and Mon-774 during their AA Tau phases (left) and aperiodic phases (right).

Of the 13 stars that presented AA Tau-like light curves in 2008, 5 (38%) were observed again in 2011, this time showing aperiodic variability due to extinction. Likewise, of the 14 stars that presented aperiodic variability in 2008, 8 (62%) were observed again in 2011, then showing periodic variability similar to AA Tau. An example of two of the stars that have undergone this change in light curve morphology is shown in Fig. 3. Of the other 10 stars that had AA Tau-like light curves, 4 were only observed in one epoch and the other 6 maintained the same behavior with the same period in both 2008 and 2011.

We attribute AA Tau-like variability to stars undergoing accretion via a stable regime, and propose that the stars in our sample that present aperiodic variability might be undergoing accretion via an unstable regime, as the one described by the MHD simulations of Kurosawa & Romanova (2013). In this scenario, the same mechanism that is responsible for lifting matter from the disk and channeling it onto accretion streams would also lift dust above the disk midplane, which could occult the star when observed at high inclinations.

If this is the case, then the change in light curve morphology points to a transition between a stable and unstable accretion regime in a matter of less than four years for 39% of the stars in our sample. Kurosawa & Romanova (2013) mention the possibility of a transition between accretion regimes, which could occur if one or a few of the parameters that influence instability change with time within a certain system, for instance, if the position of the truncation radius relative to the co-rotation radius changes. It is possible that the mass accretion rates or magnetic field configurations of these stars have changed significantly in this timescale, causing the transition.

3.2 Comparing optical and infrared light curves

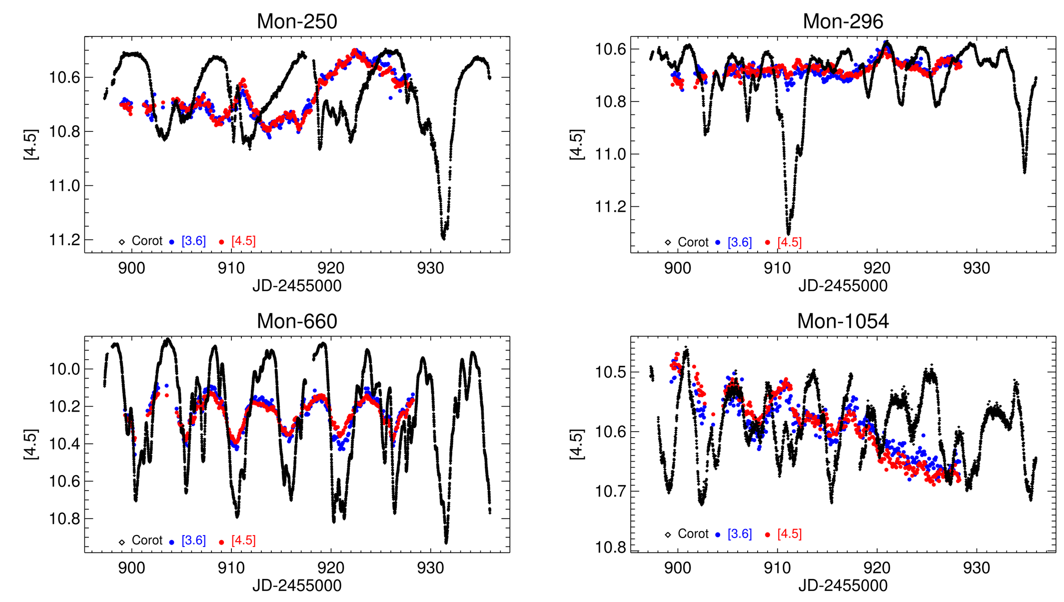

Figure 4. *Spitzer* IRAC $3.6\mu m$ and $4.5\mu m$ light curves (blue and red filled circles, respectively) overplotted on CoRoT light curves (black circles). The CoRoT and IRAC $3.6\mu m$ light curves were shifted in magnitude for easier comparison.

We compared CoRoT and *Spitzer* light curves for the stars that were observed simultaneously. Some show light curves that are very similar in the optical and IR, while others present completely different behavior in the different bands. In one case, the IR variability nearly anti-correlates with the optical (see examples in Fig. 4).

For those cases in which we observed a correlation between the two light curves, we calculated what extinction laws would be necessary to transform one into the other. We found values of A_λ/A_V between 0.28 and 0.77 (where λ is the wavelength, equal in this case to $3.6\mu m$ and $4.5\mu m$). These values are considerably higher than extinction laws typically found in the interstellar medium (ISM), of around $A_{3.6}/A_V = 0.05$ and $A_{4.5}/A_V = 0.04$. This indicates that the distribution of dust grains in the inner circumstellar disks is quite different from the ISM, possibly containing fewer small grains.

3.3 Spectral analysis

3.3.1 Veiling variability

The excess emission in UV and optical wavelengths produced in the accretion shocks causes absorption lines in the stellar spectra to appear shallower than they would for a purely photospheric spectrum. This effect is called veiling and the greater it is, the lower an absorption line's equivalent width is.

We measured the equivalent widths of the LiI 6707.8Å line (LiIEW) in the FLAMES spectra for 15 of our stars. In order to determine whether the veiling they present is variable, and whether this variability correlates in any way to the photometry, we plotted these values of LiIEW against the I-band magnitude measured on the same night (Fig. 5). For most of these stars the veiling variability is very irregular and we cannot see a clear correlation with the photometry, but for 6 stars there seems to be an increase in veiling (decrease in LiIEW) as the flux decreases. This is consistent with a scenario in which the occultations are associated with the appearance of accretion shocks on the stellar surface. It could also occur if cold spots are responsible for the photometric variability and hot spots associated with accretion shocks cause veiling variability, but we generally expect cold spots to be more stable and therefore produce light curves that are not so irregular.

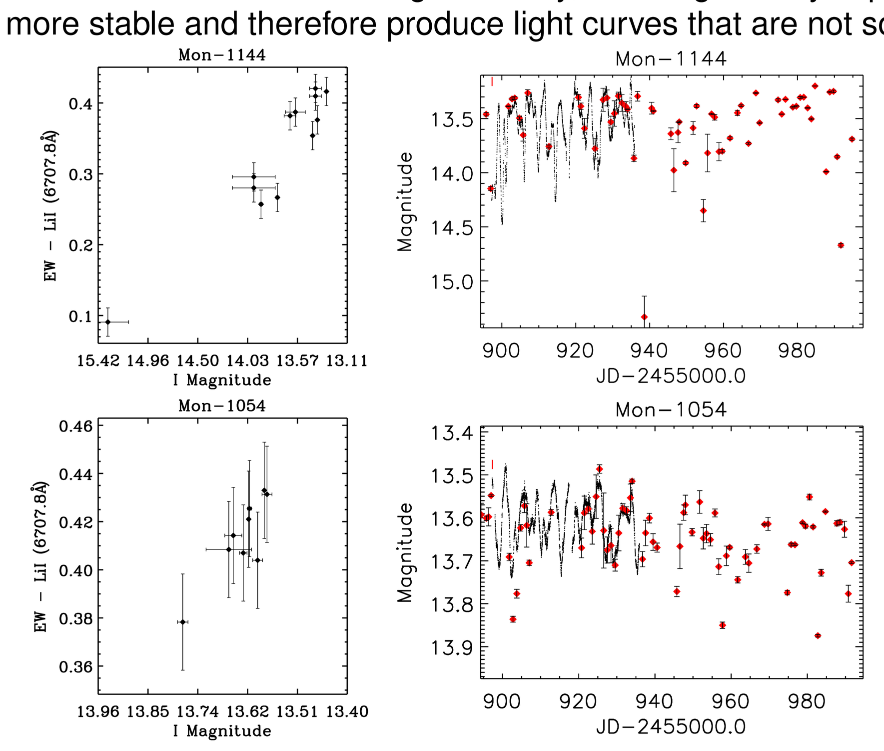

Figure 5. Left: two examples of plots of LiIEW vs. I magnitude. Right: I-band (red) and CoRoT (black) light curves of the same two stars, shifted in magnitude to coincide.

3.3.2 Mon-250

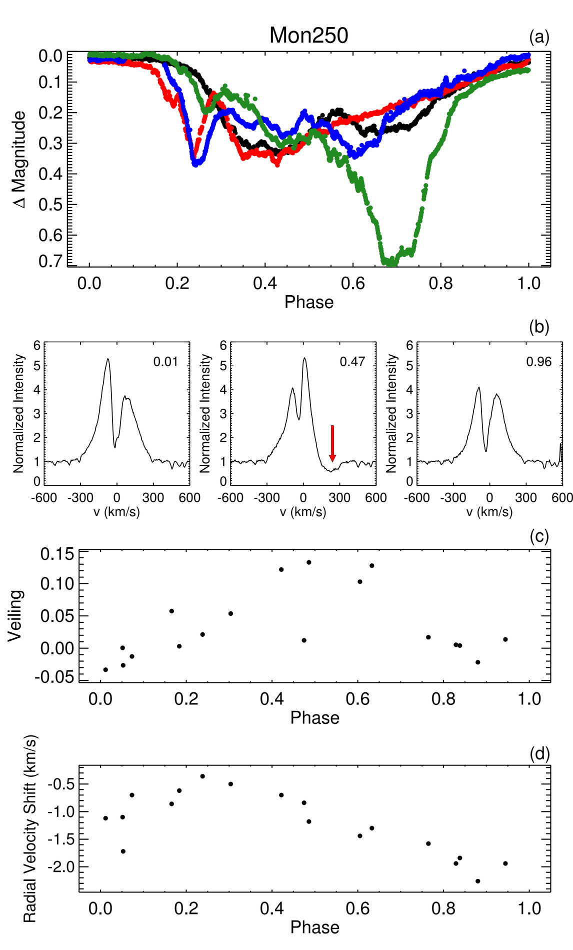

Figure 6. Mon-250. a) 2011 Corot light curve folded in phase. b) Hα line profile during different rotational phases, indicated in each panel. A redshifted absorption component seen only near phase 0.5 is indicated by a red arrow. c) Measured veiling folded in phase. d) Shift in radial velocity measured from photospheric lines in the spectra, folded in phase. In all four panels, the period found from the variability in radial velocity of photospheric lines was used to calculate the phase.

We noted a redshifted absorption component in the Hα line profile of the star Mon-250 that is only present when the light curve is at a minimum (Fig. 6b). This is evidence that the accretion funnel appears in front of our line of sight during the photometric flux dips, since the infalling material responsible for the absorption is moving away from us. This star's veiling variability also points to the appearance of accretion shocks during the occultations (Fig. 6c). With this, it seems clear that the inner disk warp, responsible for the occultations in this star's light curve, is located at the base of its accretion columns, as was suggested for AA Tau by Bouvier et al. (2007).

For this star we were also able to measure the variability in the radial velocities of photospheric lines and with this determine a rotation period of 8.6 ± 0.5 days (Fig. 6d). This value is consistent with the photometric period of 8.9 ± 0.5 days found with the 2011 CoRoT light curve, indicating that the occulting structure is located at or near the disk's co-rotation radius, as was also shown for AA Tau.

3.4 Color variability

For the periodic stars, we plotted I-band and $u-r$ light curves in phase using each star's photometric period, in order to investigate the color variability in these stars. In most cases we see a reddening during occultations, which is to be expected for extinction events. For 4 stars we see a slight bluing during a flux minimum in one or two rotation cycles, which we attribute to the appearance of hot spots associated with accretion shocks during occultations. Two stars show no significant color variability. Fig. 7 shows a few examples of these plots.

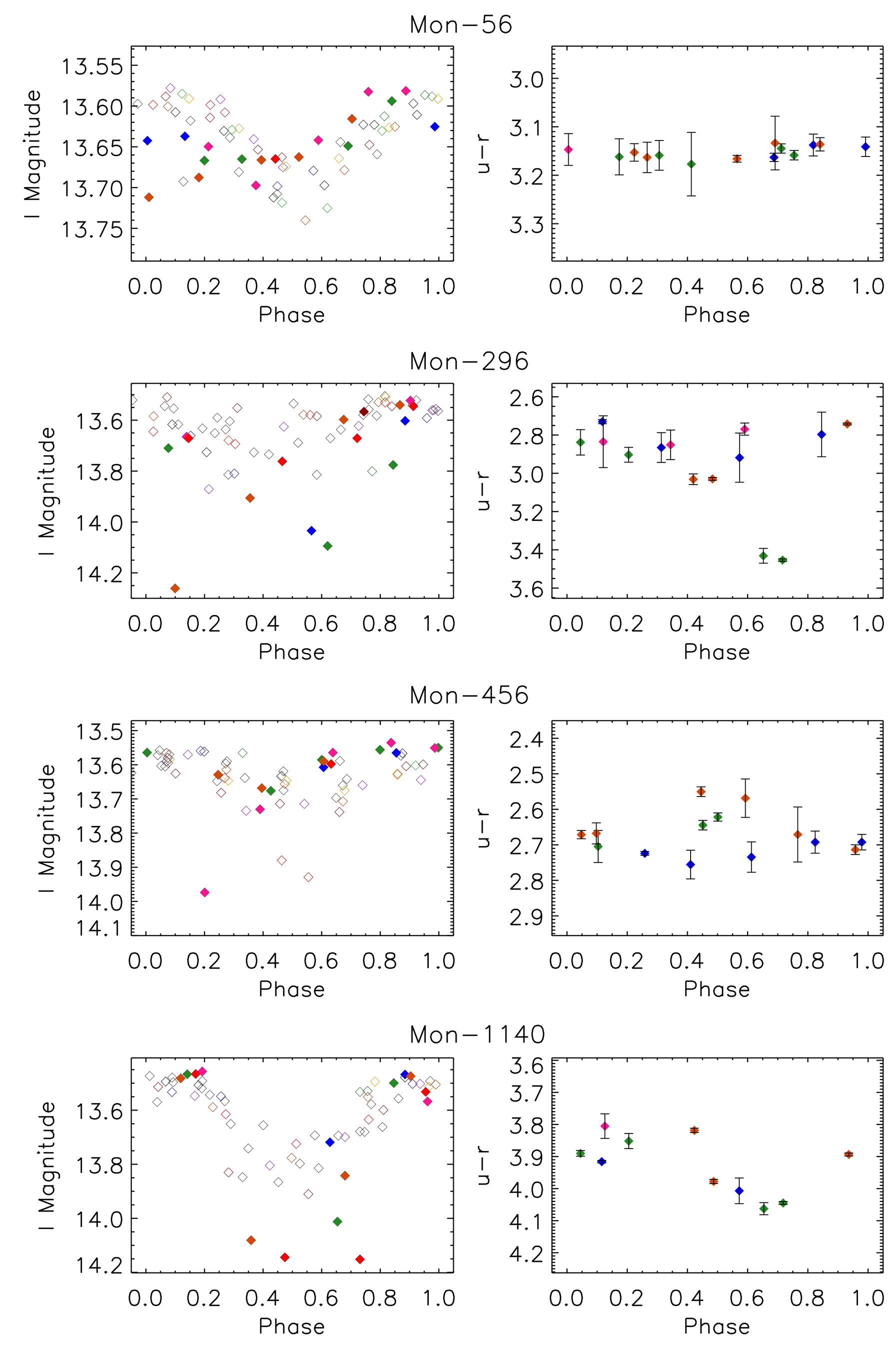

Figure 7. I-band and $u-r$ light curves folded in phase. The colors used for $u-r$ represent the same rotation cycle as filled diamonds of the same color in I.

3.5 AA Tau's occultation model

In order to apply the occultation model proposed for AA Tau to our periodic light curves, we used values of masses and radii determined by Venuti et al. (2014), and values of $v \sin i$ determined by us from the FLAMES spectra or spectra from the literature. We used these values and photometric periods to determine co-rotation radii, and to estimate the star-disk systems' inclinations. We then fixed these parameters and fitted each minimum of each light curve individually to find the warp parameters (h_{max} and ϕ_w) that best reproduced the amplitudes and widths of the dips. Fig. 8 shows examples of these fitted light curves.

We found that one star, Mon-1131, has a low inclination, which is inconsistent with the AA Tau scenario, and therefore removed it from the analysis. For the other stars, we found values of h_{max}/R_{co} between 0.10 and 0.34, and values of ϕ_w usually around $300°$, with individual cases ranging from $110°$ to a full $360°$. These values are consistent with the parameters used for AA Tau ($h_{max}/R_{co} = 0.3$ and $\phi_w = 360°$). In order to reproduce the variability of the flux dip shapes and amplitudes, the warp parameters must be variable on a timescale of days, presenting typical variations of 10 - 20% between rotation cycles.

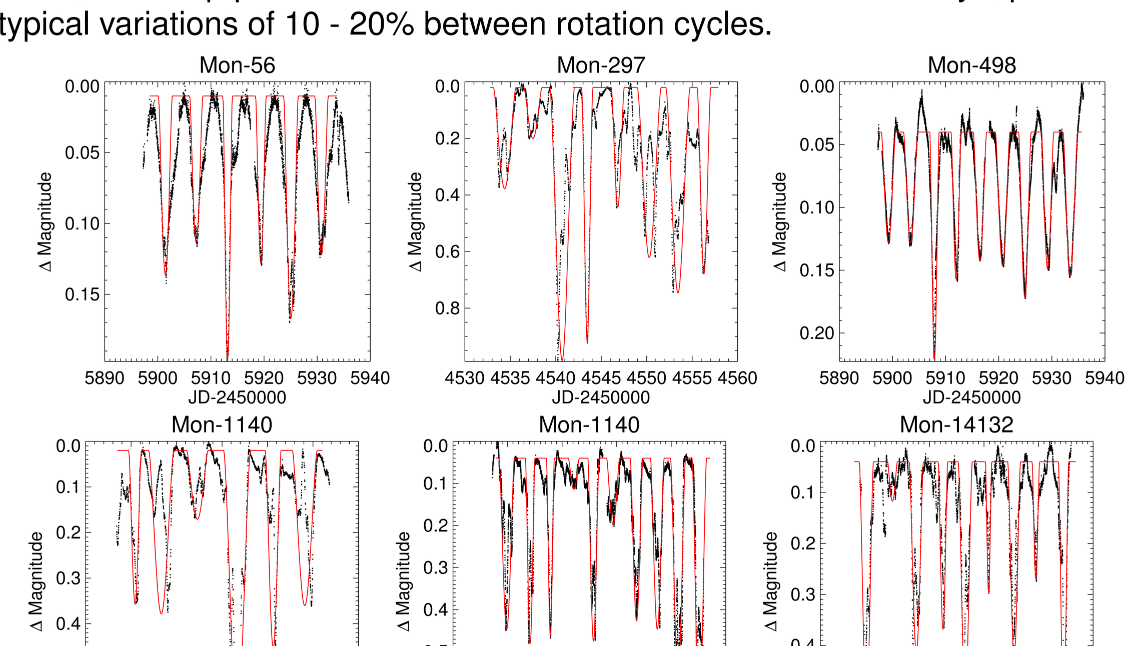

Figure 8. Examples of simulated light curves of AA Tau-like stars (red) plotted over CoRoT light curves (black).

4 Conclusions

We find indications of a possible transition between stable and unstable accretion regimes in a timescale of less than 4 years for 39% of the stars in our sample.

We find possible evidence that the dust grains in these stars' inner accretion disks are on average larger than in the ISM.

Of our 33 stars with photometric behavior dominated by obscuration of the photosphere by circumstellar dust, we find that 8 show evidence that the extinction events are associated with accretion shocks. This could indicate that the occulting structures are located at the base of accretion columns.

For 23 stars with AA Tau-like light curves, 22 appear to be consistent with the AA Tau scenario, in which an inner disk warp located at the co-rotation radius occults the star periodically. The model proposed to explain AA Tau's light curve is capable of reproducing the amplitudes and widths of these 22 stars' light curves using similar parameters to the ones found for AA Tau itself. These parameters are shown to be variable on rotation timescales, probably reflecting the dynamic nature of the disk-magnetosphere interaction.

Acknowledgements

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