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, 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 and different techniques, we can attempt to better understand the processes that occur in this region.

1.1 AA Tau and stars with AA Tau-like light curves

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, described in Fig. 1, was proposed to explain these dips.

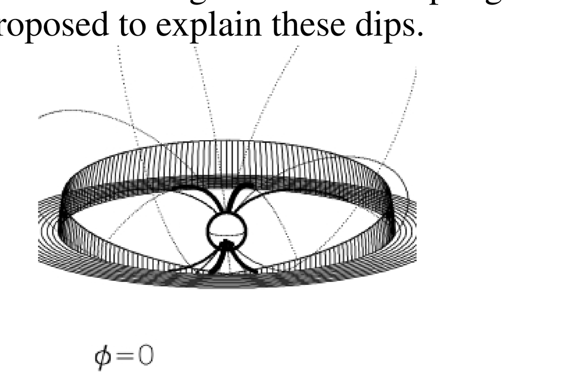

Figure 1. A clump of given maximum height h_{max} and azimuthal extension ϕ_w, present at the co-rotation radius R_{co}, periodically occults the stellar photosphere of a system seen at inclination i as the system rotates. Figure from Bouvier et al. (1999)

In March 2008 the CoRoT satellite observed the young open cluster and rich star forming region NGC 2264 for 28 days uninterruptedly. Among the young stellar objects (YSOs) observed, Alencar et al. (2010) found many CTTSs with light curves resembling that of AA Tau's 1995 light curve (Fig. 2). Their behavior was attributed to the same phenomenon as the one proposed for AA Tau.

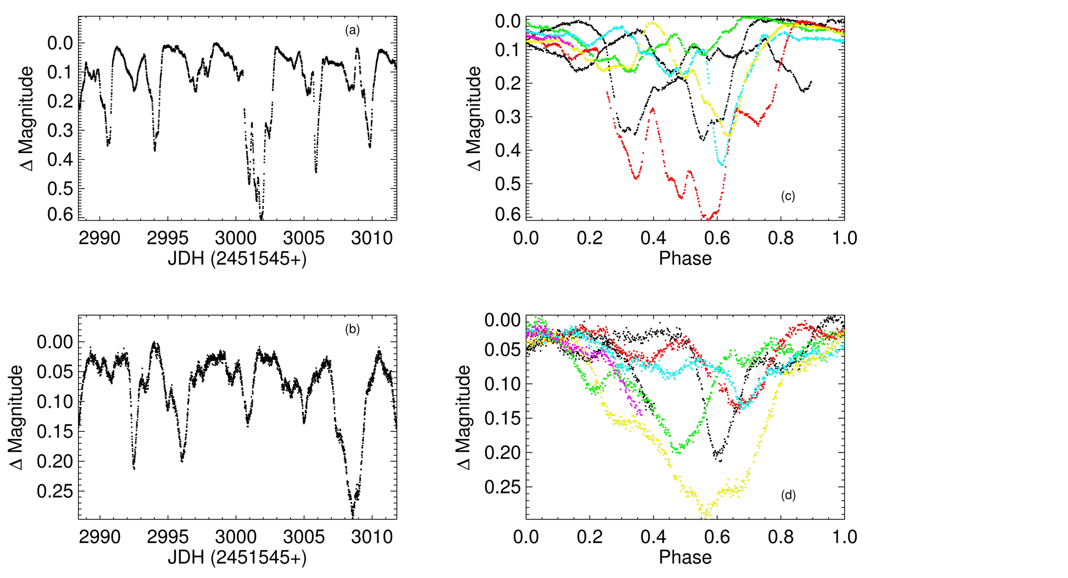

Figure 2. Left: AA Tau-like CoRoT light curves found in NGC 2264 by Alencar et al. (2010). They present a relatively stable maximum brightness, interrupted by quasi-periodic flux dips. We attribute them to occultations of the photosphere by circumstellar material, possibly located in an inner disk warp. Right: the same light curves folded in phase. Different colors represent different rotation cycles.

2 Observations in NGC 2264

After the success of the 2008 CoRoT observations, NGC 2264 became the object of a new and more complete observational campaign in December 2011, entitled the "Coordinated Synoptic Investigation of NGC 2264" (CSI2264, Cody et al., 2014). This campaign included observations from

- the *Spitzer* space telescope for 30 days in the IRAC 3.6μm and 4.5μm bands;
- the CoRoT satellite for another 40 days, simultaneously with *Spitzer*;
- the CFHT MegaCam in the u- and r-bands for 14 days, approximately one month after the CoRoT and *Spitzer* observations;
- the FLAMES multi-object spectrograph on the VLT, obtaining 20-22 high- and medium-resolution spectra, up to 6 of which were simultaneous with CoRoT, for 58 CTTSs; and
- the USNO 40" telescope in the I-band for nearly four months, spanning the CoRoT, *Spitzer*, CFHT, and FLAMES observations.

This campaign provided us with simultaneous photometric and spectroscopic information in a wide range of wavelengths for hundreds of YSOs.

New CTTSs with AA Tau-like light curves were found, besides many others with similar photometric variability, but that were not periodic. **We attribute this aperiodic behavior to occultations of the photosphere by material randomly lifted above the disk midplane because of instabilities in the disk.** Of the 159 CTTSs observed by CoRoT in 2008 and/or 2011, 33 had light curves dominated by extinction events. Of these, 23 showed AA Tau-like behavior in one epoch or both.

3 Analysis and Results

3.1 Periodic and aperiodic photometric behavior

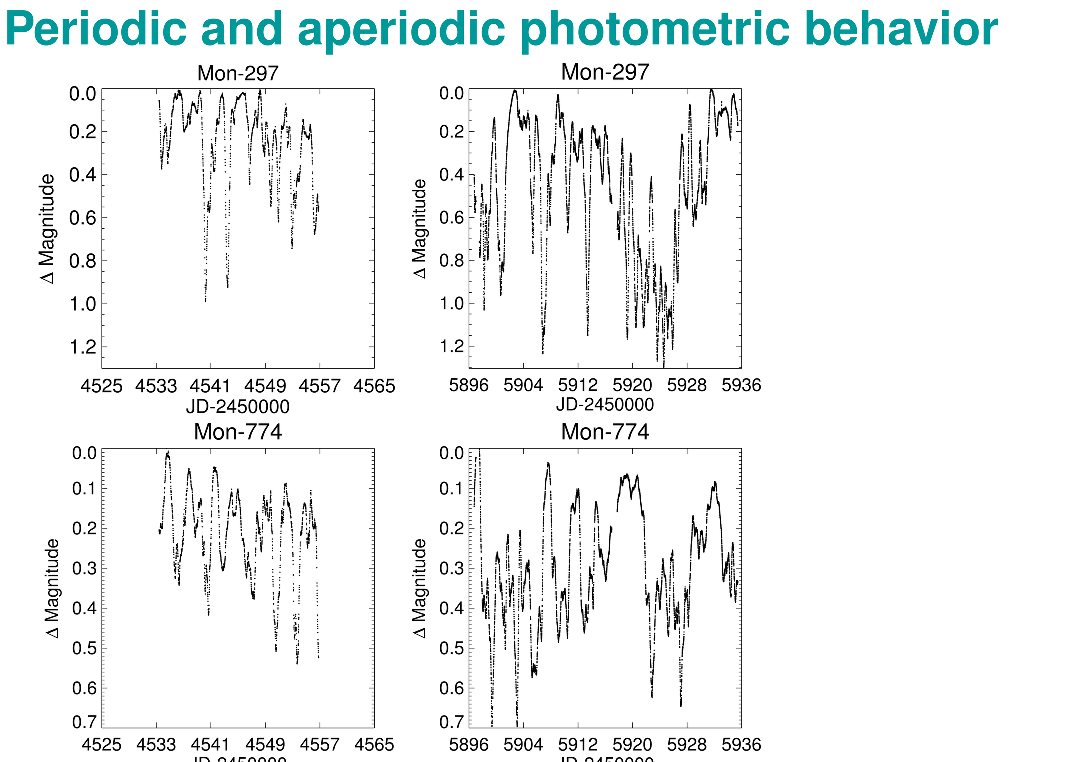

Figure 3. Corot light curves of Mon-297 and Mon-774 during their AA Tau phases (left) and aperiodic phases (right).

Of the 13 stars with AA Tau-like light curves from 2008, 5 (38%) presented aperiodic variability due to extinction in 2011, while 8/14 (62%) of the stars with aperiodic variability in 2008 showed AA Tau-like light curves in 2011. Two examples of stars that have undergone this change in light curve morphology are shown in Fig. 3. Six stars with AA Tau-like light curves maintained this behavior with the same period in both epochs, and four were only observed in one epoch.

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**. According to Kurosawa & Romanova (2013), a transition between accretion regimes could occur if one or a few of the parameters that influence instability change with time within a certain system, for instance, the position of the truncation radius relative to the co-rotation radius. 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 Spectral analysis

3.2.1 Veiling variability

The excess UV and optical emission 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 if this variability correlates with the photometry, we plotted these values of LiIEW against I-band magnitudes measured on the same nights (Fig. 4). Most of these stars have very irregular veiling variability, 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 were responsible for the photometric variability and there were hot spots associated with them, but we expect cold spots to be more stable and therefore produce light curves that are not so irregular.

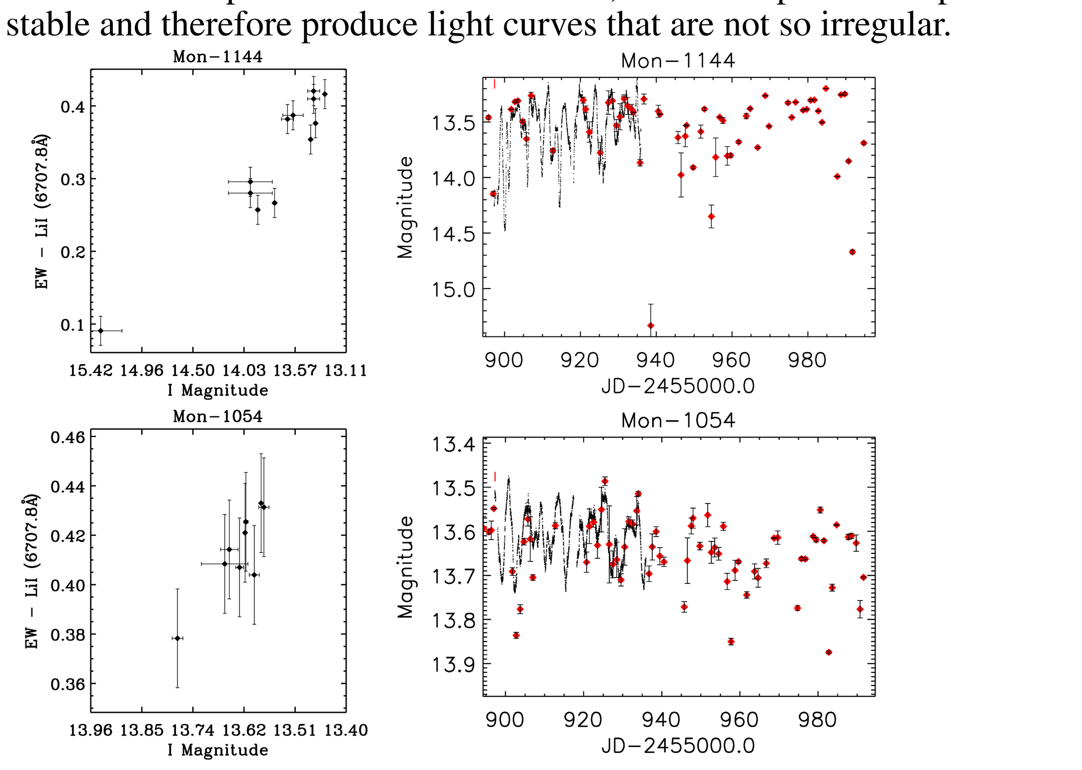

Figure 4. Left: plots of LiI equivalent widths vs. I magnitude. Right: I-band (red) and CoRoT (black) light curves of the same stars, shifted in magnitude to coincide. For these stars the veiling increases (LiIEW decreases) as the flux decreases. This may indicate that accretion shocks appeared on the stellar surface during the occultations.

3.2.2 Mon-250

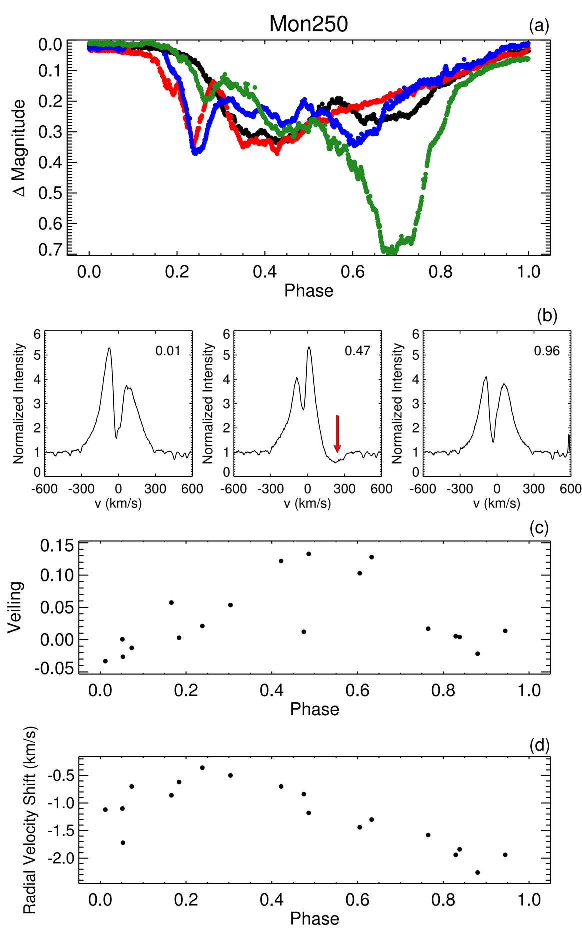

Figure 5. Mon-250.

a) 2011 Corot light curve folded in phase (different colors represent different rotation cycles).

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, showing that it often increases during the occultations.

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. 5b). 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. 5c). 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 able to measure variability in the radial velocities of photospheric lines and with this determine a rotation period of 8.6 ± 0.5 days (Fig. 5d). 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.

3.3 Comparing optical and infrared light curves

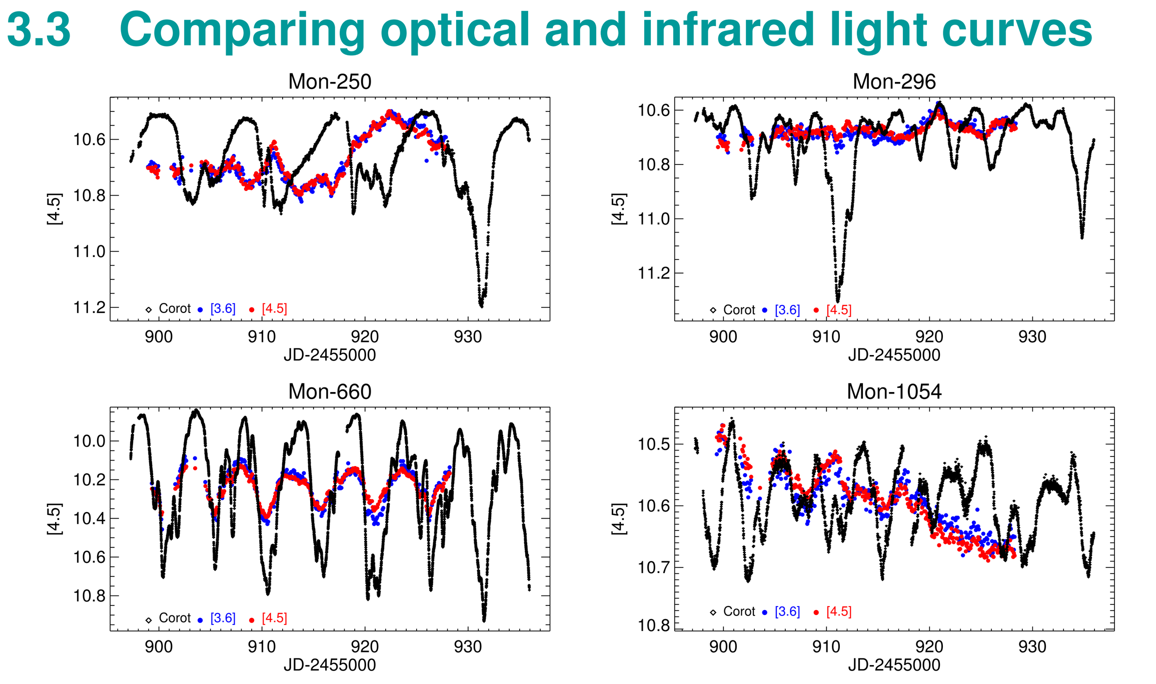

Figure 6. *Spitzer* IRAC 3.6μm and 4.5μm light curves (blue and red, respectively) overplotted on CoRoT light curves (black), with CoRoT and IRAC 3.6μm light curves shifted in magnitude for easier comparison. Some show very similar trends in the optical and IR, while others show completely different behavior. The star Mon-250 seems to show an anti-correlation between optical and IR variability.

We compared CoRoT and *Spitzer* light curves for the stars that were observed simultaneously (see Fig. 6 for examples). For those cases in which the two light curves show some correlation, we calculated what extinction laws would be necessary to transform one into the other, assuming an optically thin regime. We found values of A_λ/A_R between 0.28 and 0.77 (where $\lambda = 3.6\mu$m and 4.5μm). These values are considerably higher than extinction laws typically found in the interstellar medium (ISM), of around $A_{3.6}/A_R = 0.07$ and $A_{4.5}/A_R = 0.05$. **This indicates that the distribution of dust grains in inner circumstellar disks is quite different from the ISM**, possibly containing fewer small grains.

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 (see Fig. 7 for examples). In most cases we see a reddening during occultations, which can 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.

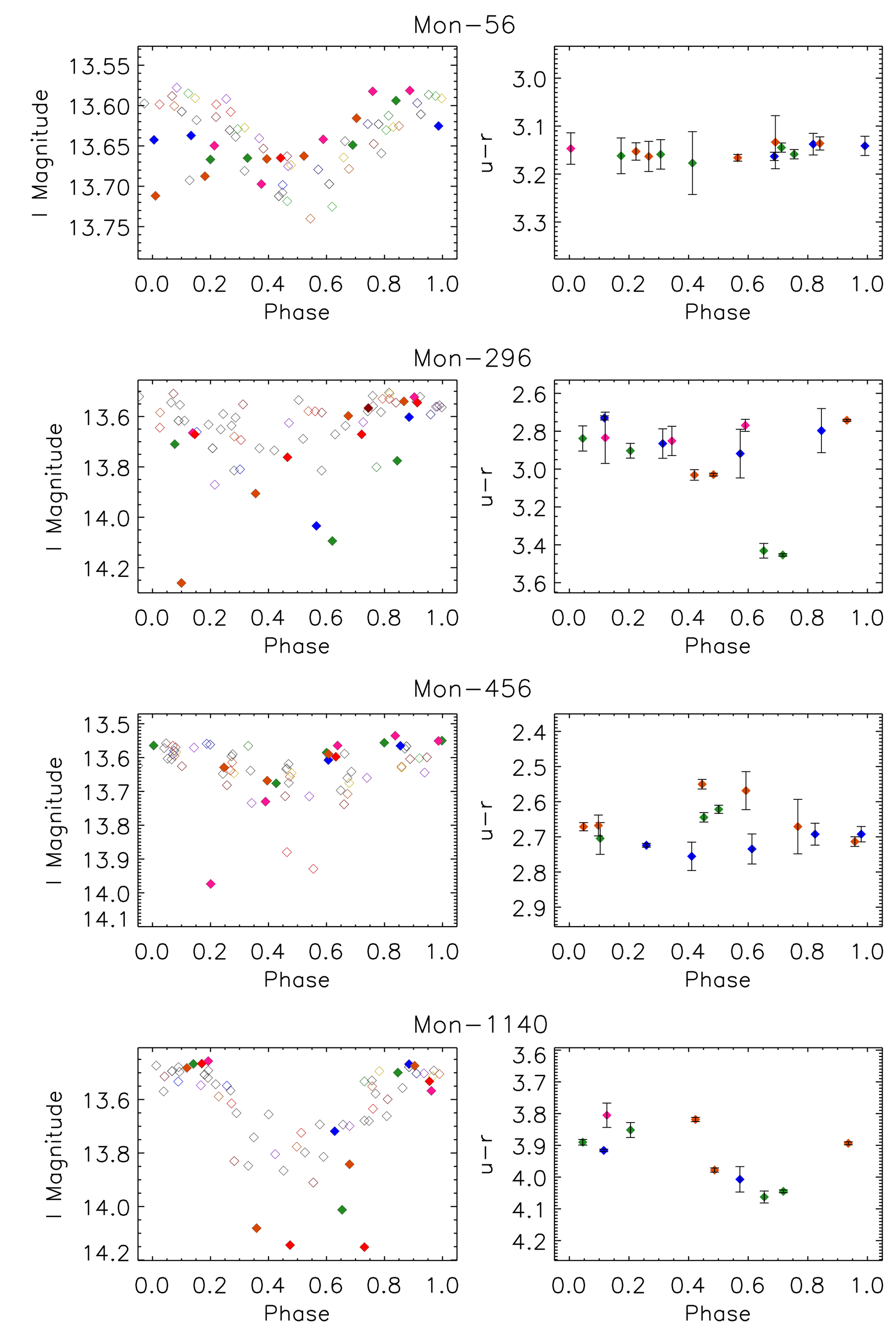

Figure 7. I-band and $u - r$ light curves folded in phase. The colors used for $u - r$ represent the same rotation cycle as filled diamonds of the same color in I. Note that the star Mon-456 shows a slight bluing during two rotational phases, which we interpret as accretion shocks appearing during occultations.

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 masses and radii determined by Venuti et al. (2014), values of $v \sin i$ determined by us from the FLAMES spectra or spectra from the literature, 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.

One star, Mon-1131, was found to have a low inclination, inconsistent with the AA Tau scenario. Therefore we 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**.

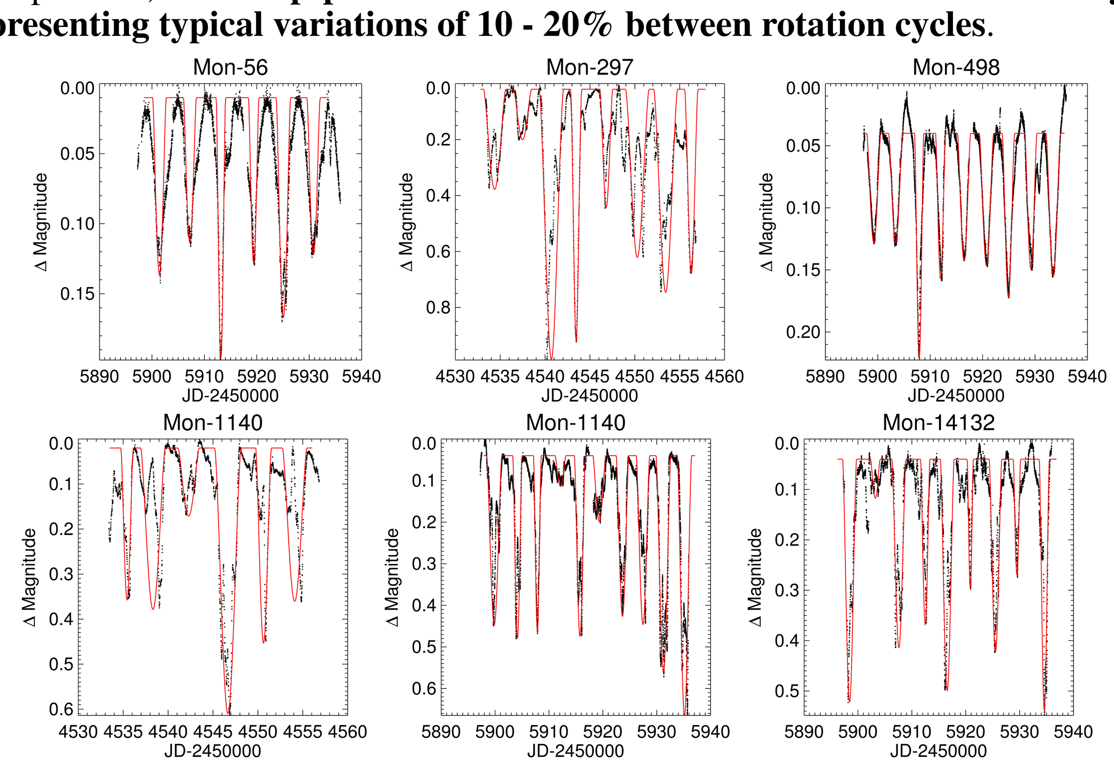

Figure 8. Light curves reproduced by the occultation model of Bouvier et al. (1999, red) plotted over AA Tau-like CoRoT light curves (black).

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 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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