The inner disks of classical T Tauri stars in NGC 2264

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Abstract

NGC 2264 is a young (~ 3 Myr) stellar cluster that was observed twice by the CoRoT satellite, for 23 days in 2008 and 40 days in 2011. Simultaneouslys with the 2011 CoRoT observations, a multiwavelength campaign was organized that included 30 days of Spitzer observations at 3.6 and 4.5 microns, 3.5 days of Chandra data, VLT FLAMES spectroscopy and U band photometry from Megacam (CFHT). We obtained simultaneous high precision light curves in the optical and near IR for more than 500 cluster members, about 150 of which are classical T Tauri stars. As shown in the first CoRoT campaign, a fraction of the accreting systems exhibit optical light curves with deep minima that vary substantially in width and depth in a rotational timescale. These light curves are interpreted as being due to an inner disk warp that eclipses the star as the system rotates, as observed in AA Tau, a well studied CTTS seen at high inclination. This warp is thought to be created by the star-disk interaction mediated by a stellar magnetic field inclined with respect to the stellar rotation axis. The observed variability indicates that the star-disk interaction is dynamic and the occulting material is inhomogeneous and located close to the co-rotation radius of the star-disk system. We present the photometric and spectroscopic analysis of the AA Tau-like CTTSs observed in NGC 2264. Initial light curve model results indicate that an inner disk warp located near the co-rotation radius can indeed explain the observed variability and that, if the variability is attributed to extinction alone, the properties of the dust in the inner disk are substantially different from the ISM.

1 Introduction

Classical T Tauri stars (CTTSs) are young (~ 1 Myr), low mass stars (M ≤ 2 $M_{\odot}$) surrounded by a circumstellar disk from which they are still accreting. They exhibit observational characteristics of accretion, such as:

- ultraviolet and optical excess with respect to the photosphere
- strong and wide emission lines (Hα , Hβ , He I,...)

The accretion disk is disrupted at a few stellar radii from the stellar surface ($r_{tr} \leq 0.1$ AU), due to the presence of the central star's magnetic field. The accreting gas follows the magnetic field lines from the truncation radius to the star, forming accretion columns and hits the stellar surface creating hot spots (Bouvier et al. 2007b). The gas is also ejected from the system along open magnetic field lines as a wind, forming a collimated jet. The inner part of the star-disk system is shown in the Figure below.

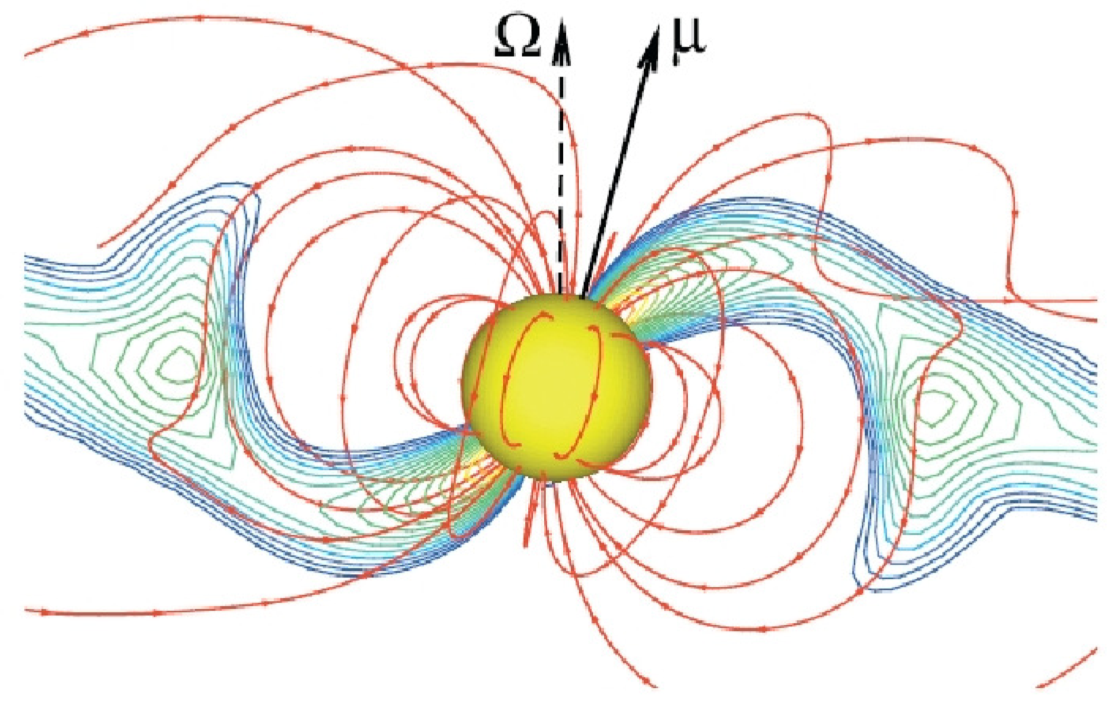

Figure 1. MHD simulation of accretion onto a CTTS. This simulation shows the inner disk warp that exists due to the inclination between of the magnetic field axis (μ) and the rotational axis of the star (Ω). The contour lines show the plane cross section of the density distribution inside the funnel. The density changes exponentially from $\rho = 0.2$ (blue) to $\rho = 2.0$ (red) close to the stellar surface (Romanova et al. 2004). Red lines with arrows show selected magnetic field lines.

AA-Tau is one of the best studied CTTS (Bouvier et al. 2007a). It exhibits a light curve with a flat maximum interrupted by minima that vary in width and depth from cycle to cycle as the system rotates. These minima are explained by eclipses due to an inner disk warp created by the inclination of the magnetic field axis with respect to the rotational axis of the star.

NGC 2264 is a young stellar cluster (~ 3Myr), located at a distance of ~ 760 pc, where the star formation process is still happening. We searched for AA-Tau-like light curves in NGC 2264 to infer the characteristics the inner disk in such systems.

2 Observation

The CoRoT satellite observed NGC 2264 in two epochs. The first was during 23 days in 2008 (from March 7 to 30), where photometric data was obtained for at least ~ 300 known cluster members. The second time, NGC 2264 was observed during 40 days (from December 2, 2011 to 10 January, 2012). Simultaneously with the 2011 CoRoT data, the cluster was observed with Spitzer at 3.6 and 4.5 μm for 30 days, and 3.5 days with Chandra. We also obtained VLT FLAMES spectroscopic data during 20 days and U band photometry from Megacam (CFHT). For more information about the NGC 2264 campaign, see Cody et al. (2013).

3 First Results

Among the NGC 2264 cluster members, 304 are likely CTTSs, according to the following criteria:

- Hα equivalent width larger than a threshold given by White & Basri (2003),
- Hα width at 10% of maximum intensity larger than 270 km/s, or
- ultraviolet excess in the CTTS range, as defined by Venuti et al (2013), based on U band photometry from Megacam (CFHT)

Among the CTTSs, 86 stars were observed by CoRoT in 2008 and 145 stars were observed in 2011. The 2008 CTTS light curves (LCs) were classified morphologically as spot-like, AA-Tau-like or non-periodic (NP), as shown in Alencar et al. (2010). The spot-like LCs display sinusoidal variations, due to large cold spots at the stellar surface, that are very stable in the timescale of our observations. The AA-Tau-like LCs exhibit a well defined maximum interrupted by periodic minima that vary in width and depth from cycle to cycle, like AA Tau itself. From a total of 145 CTTSs observed by CoRoT in 2011, about 18 stars were classified as having AA-Tau-like LCs against 23 in 2008 (Alencar et al. 2010). Non-periodic light curves may be due to stochastic accretion or circumstellar disk obscuration. Figure 2 show examples of the observed light curves.

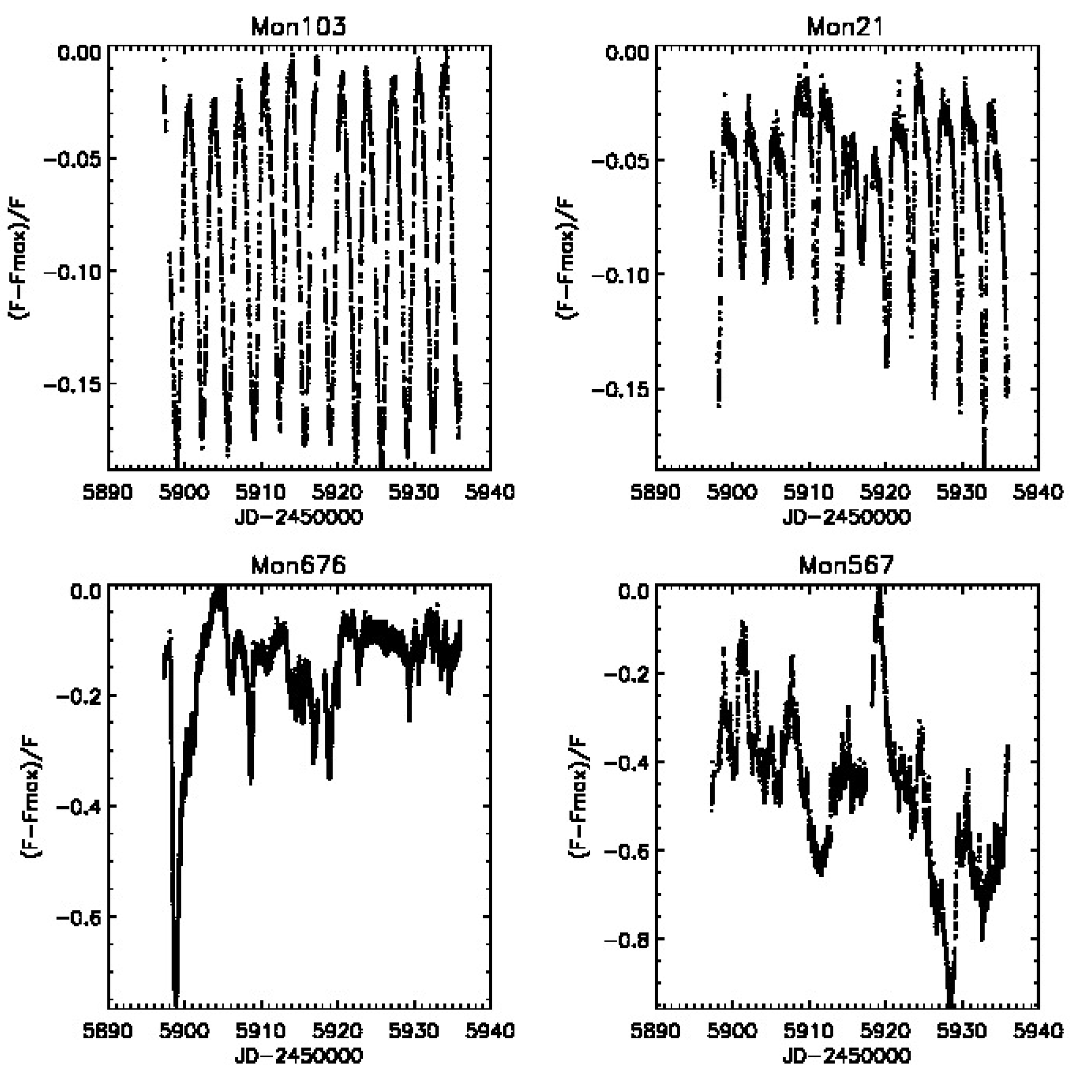

Figure 2. CoRoT light curves of CTTSs from 2011. From left to right, top to bottom: Spot-like, AA-Tau-like, non-periodic obscuration by circumstellar material, and a non-periodic light curve dominated by stochastic variation in mass accretion rate.

Many of the stars observed by CoRoT in 2008 presented Spitzer observations from the literature Teixeira et al. (2012), which allowed us to compute α_{IRAC} index, as proposed by Lada et al. (2006). α_{IRAC} is the slope of the spectral energy distribution between 3.6μm and 8μm, which allows a classification of the inner disk, as shown in Fig. 3. From Figure 3, we see that AA-Tau-like stars present inner dusty disks, as expected, since their light curve variability should be dominated by circumstellar dust extinction due to an inner disk warp.

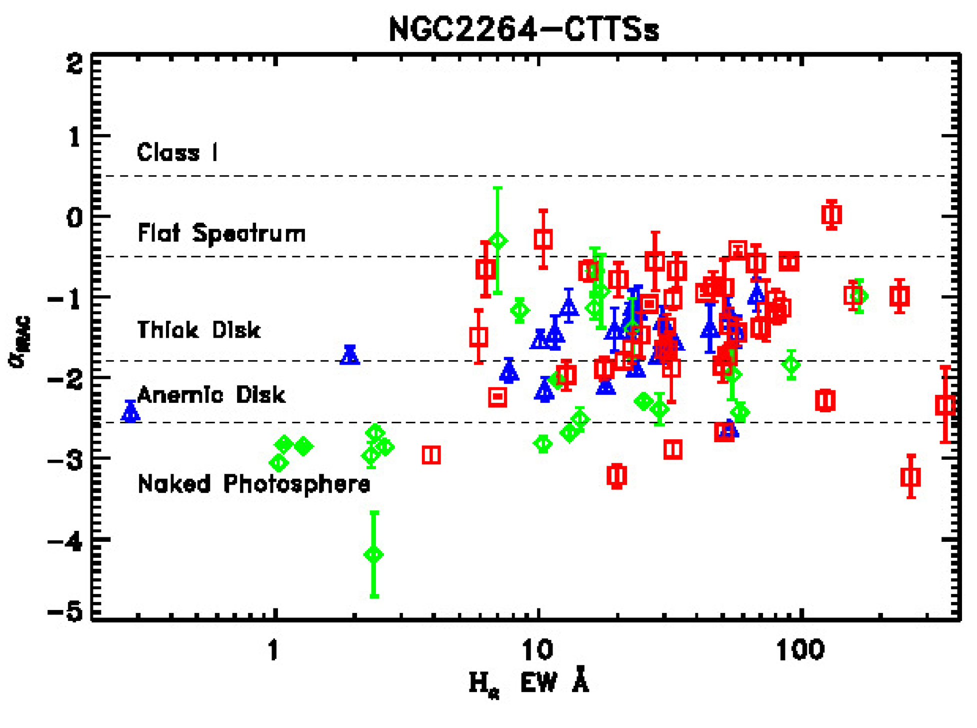

Figure 3. CTTSs observed by CoRoT with data from Spitzer in the literature. Squares correspond to non-periodic LCs, diamonds correspond to spot-like LCs and triangle to AA-Tau-like LCs, in at least one of the two epochs of observations.

The period distribution of CTTSs is shown in Figure 4. The spot-like LC period is the rotational period of the star, since cold spots are located at the stellar surface. In both epochs, most AA-Tau-like stars presented periods within the range of the stellar rotational periods of CTTSs. Therefore, the material that obscured the star should not be located very far from the corotation radius (Alencar et al. 2010).

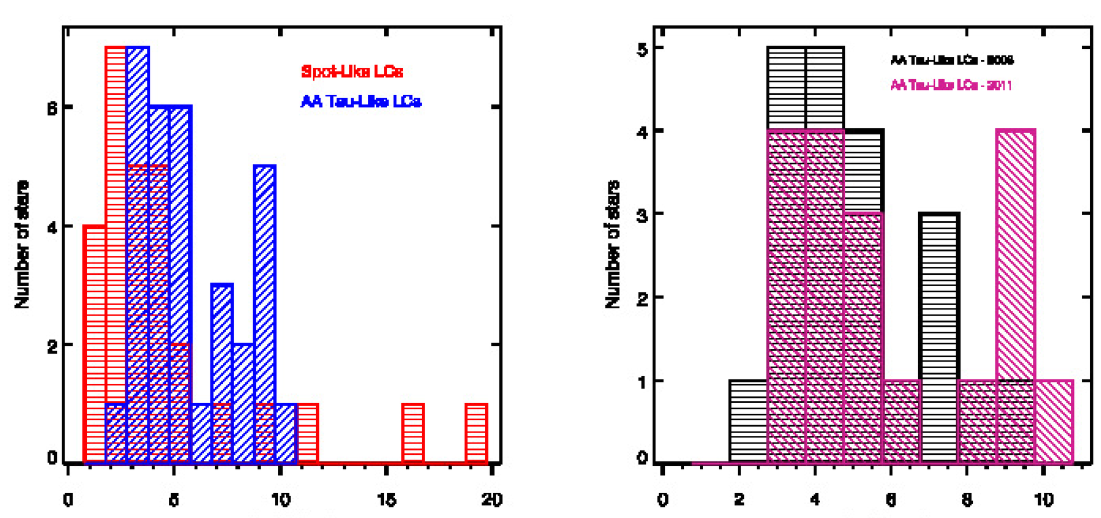

Figure 4. *Left*: distribution of periods of all the periodic CTTSs in 2008 and 2011. Spot-like periods are shown in red and AA-Tau-like periods in blue. *Right*: Period distribution of AA Tau-like stars in 2008 and 2011. This figure shows that some stars changed their LC type or their measured period (see figures 5 and 6)

Table1. Parameters for the occultation model

Parameter	Mon250-2008	Mon250-2011	Mon297-2008
Inner Disk Radii (R_*)	11.32	11.32	4.75
Inclination of the System (°)	82	82	65
Height of the Warp (R_*)	1.18-1.72	1.19-1.53	1.46-2.13
Azimuthal Extension (°)	360	360	220-360

We preliminarily applied, to AA-Tau-Like LCs, a model based on occultation by circumstellar material (Bouvier et al. 1999) to verify if it is possible to explain the observed variability as being due to eclipses of the star by an inner disk warp, as observed in AA Tau star. The figures bellow show the LC of two stars that present AA Tau-like behavior in at least one epoch (black), along with the LC simulated by the occultation model (red). Knowing the inner disk radii and inclination of the stellar systems, we were able to individually model each minimum of each LC to find the values of warp height and azimuthal extension that best reproduced the observed LCs. The parameters are given in Table 1. These simulated LCs show that material in the inner part of the circumstellar disk can be the main cause of the photometric variability of such systems.

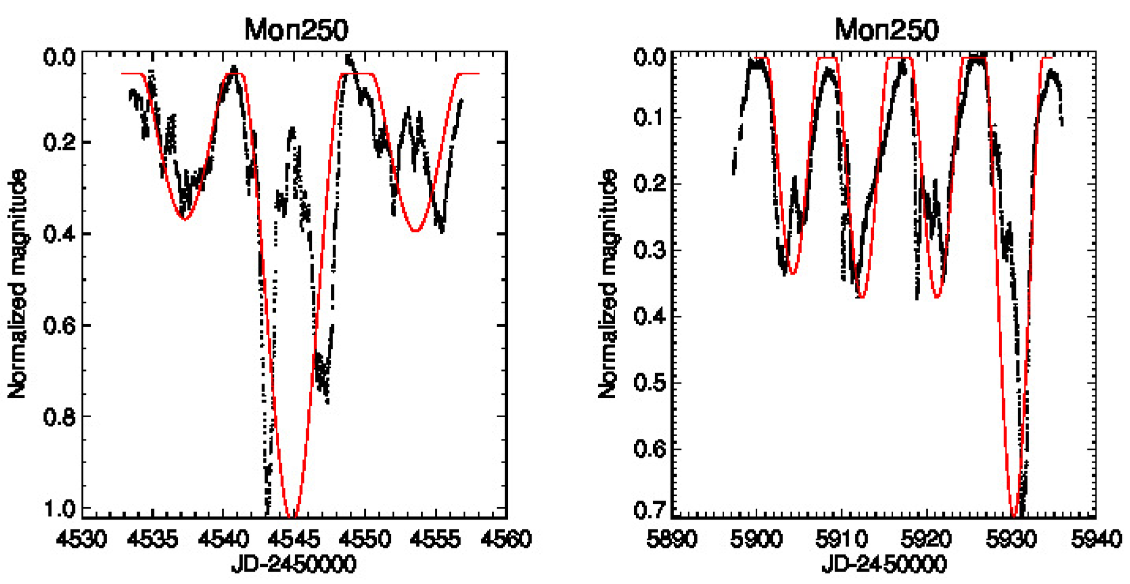

Figure 5. Red lines show the best fit using the occultation model (Bouvier et al. 1999) for the 2008 (left) and 2011 (right) CoRoT observations of Mon250. This star presented AA-Tau-like LCs in both observed epochs, but in 2008 the light curve was much more irregular than in 2011, which lead to a wrong period determination of 4.16 days. In 2011 the period of 8.89 days is clearly recovered. AA Tau-like light curves are often strongly variable and this can make it hard to precisely determine periods for such systems.

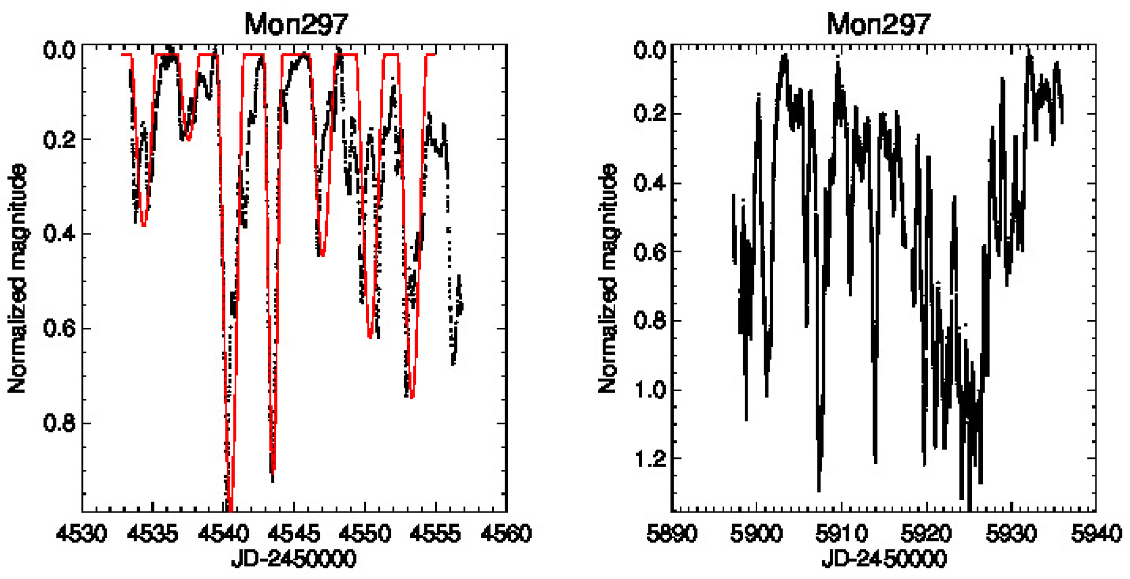

Figure 6. This star displays AA-Tau-like LC only in 2008 (left). In 2011 the LC was not found to be periodic (right).

4 Conclusions

The dynamic star-disk interaction observed in AA Tau may be common between CTTSs. 32 of the 145 among CTTSs show AA Tau-like light curves in 2008 or 2011 or both.

The photometric minima of the AA Tau-like systems are caused by material accumulated in the inner disk due to the interaction between the inclined stellar magnetosphere and the inner disk region, close to the co-rotation radius.

Among the stars that maintained AA Tau-like behavior in 2008 and 2011, the values of warp height and azimuthal extension found in each epoch are very similar. This shows that the structure responsible for the photometric minima is stable over the course of a few years.

From one cycle to another, the warp height presents mean variations of 14% in the AA Tau-like light curves, showing that it is very dynamic in a day timescale. The azimutal extensio, however, only presents about 6% of variability from cycle to cycle.

Acknowledgments

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