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Analysis of star-disk interaction in young stellar systems

N.N.J. Fonseca[1,a], S.H.P. Alencar[1] and J. Bouvier[2]

[1] *Departamento de Física – ICEx – UFMG, Av. Antônio Carlos, 6627, 30270-901, Belo Horizonte, MG, Brazil*
[2] *UJF-Grenoble 1 / CNRS-INSU, Institut de Planétologie et d'Astrophysique de Grenoble (IPAG) UMR 5274, Grenoble, F-38041, France*

Abstract. We present preliminary results of the study of star-disk interaction in the classical T Tauri star V354 Mon, a member of the young stellar cluster NGC 2264. As part of an international campaign of observation of NGC 2264 organized from December 2011 to February 2012, high resolution photometric and spectroscopic data of this object were obtained simultaneously with the Chandra, CoRoT and Spitzer satellites, and ground-based telescopes, as CFHT and VLT at ESO. The optical and infrared light curves of V354 Mon show periodic brightness minima that vary in depth and width every rotational cycle. We found evidence that the Hα emission line profile changes according to the period of photometric variations, indicating that the same phenomenon causes both modulations. Such a correlation between emission line variability and light curve modulation was also identified in a previous observational campaign on the same object, where we concluded that material non-uniformly distributed in the inner part of the disk is the main cause of the photometric modulation. This assumption is supported by the fact that the system is seen at high inclination. It is believed that this distortion of the inner part of the disk results from the dynamical interaction between the stellar magnetosphere, inclined with respect to the rotation axis, and the circumstellar disk, as also observed in the classical T Tauri star AA Tau, and predicted by magnetohydrodynamic numerical simulations. A model of occultation by circumstellar material was applied to the photometric data in order to determine the parameters of the obscuring material during both observational campaigns, thus providing an investigation of its stability on a timescale of a few years.

1 Introduction

Classical T Tauri stars (CTTSs) are young (~ 1 Myr), low-mass ($M \leq 2\ M_\odot$) stars in the pre-main sequence phase, being of great interest as prototypes of young solar type stars. They show photometric and spectroscopic irregular variability, strong Hα emission with redshifted and blueshifted absorptions, and forbidden emission lines, such as [OI], [SII], and [NII]. They also present strong magnetic fields (~ few kG) and emission excess with respect to the stellar photosphere at wavelengths from X-rays to radio. These general features are explained by magnetospheric accretion models [1–4], in which a young star accretes material from a circumstellar disk. The disk is disrupted at a few stellar radii by a strong stellar magnetic field and the gas from the inner disk is channeled on to the stellar surface along field lines, creating accretion funnels. Hot spots are produced in the photosphere by

[a] e-mail: nath@fisica.ufmg.br

the shock of material at free fall velocity. Material is also ejected from the system as a disk wind. According to this model, the hot spots produce the optical and UV excesses, the broad emission lines and the Hα redshifted absorption are generated in the accretion flow, while the forbidden emission lines and the Hα blueshifted absorption are produced in the ionized wind, and the circumstellar disk is responsible for the observed infrared excess.

One of the best studied CTTS is AA Tau, observed for a month during three different campaigns [5–7]. This star presents an almost constant brightness level, interrupted by periodic atenuation events. A deformation in the inner part of the circumstellar disk, produced by a misalignment between the rotation and the magnetic field axis, was identified as the cause of the observed photometric variability, occulting the stellar photosphere as the system rotates. The brightness modulation changes its shape on a timescale of a few weeks in each campaign to a few years from campaign to campaign, showing an evolution in the structure of the deformation. In March 2008, an aditional program of the CoRoT satellite observed the young cluster NGC 2264 for 23 days uninterruptedly. Alencar et al. [8] concluded that 28% of the observed CTTSs exhibit the same type of variability as AA Tau, showing that the occultation by circumstellar material as the main cause of photometric variability is common among young stars.

From December 2011 to January 2012, an international campaign was organized to observe NGC 2264 simultaneously with several satellites: CoRoT and MOST for 39 days in the optical, Spitzer for 29 days in the infrared, and Chandra for 3.5 days in the X-rays. Observations with ground-based telescopes were also obtained: spectroscopy with VLT/Flames for 20 nights, *ur* bands with CFHT/Megacam for 15 nights in February 2012, I band with USNO for ~ 70 nights from November 2011 to March 2012, and others. Therefore, this campaign will enable a comprehensive analysis of the phenomena that occur in young stars, covering simultaneously a wide range in wavelength on a long timescale.

2 V354 Mon

V354 Mon is a K4V CTTS member of NGC 2264 that was observed by CoRoT in the 2008 and 2011 campaigns. In 2008, simultaneous échelle spectroscopy was obtained with the SOPHIE spectrograph at the Observatoire de Haute Provence (CNRS, France). In this Section, we analyse the data obtained for V354 Mon in the 2011 multiwavelength campaign, comparing them with the results from the 2008 data (Fonseca et al. in preparation).

2.1 Photometry

The CoRoT light curves of the two campaigns (figure 1, left) show the same morphological characteristics, with minima that vary in depth and width every rotational cycle. V354 Mon exhibits simultaneous eclipses in u and r bands of CFHT (figure 1, right), but with a larger amplitude in u (2.23 ± 0.01) than in r (1.57 ± 0.01). No UV excess emission was measured, indicating that the hot spot may be eclipsed most of the time by the accretion flow.

The photometric modulation in the infrared is very similar to the optical (figure 1, bottom left), but the amplitude of variation is two to three times smaller in the infrared. If we consider that the photometric variation is caused only by dust extinction, it is possible to reproduce the infrared variability using the CoRoT light curve and assuming that the extinction ratio has a constant value of $A_{4.5\mu m}/A_V$ = 0.25 (figure 2, left). This value is 5 times higher than expected for extinction by interstellar dust [9], which would indicate that the dust grains in the disk are larger than in the interstellar medium.

Combining the Corot, CFHT, and USNO datasets (figure 2, right), we have a photometric coverage for more than 100 days, which enables a good determination of the period, (5.21 ± 0.04) days. This

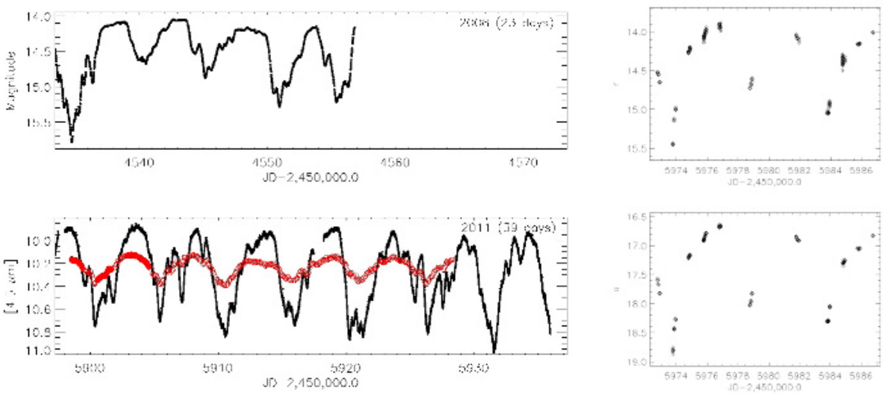

Figure 1. Left. CoRoT light curves obtained in 2008 (top) and 2011 (bottom), compared with 4.5 μm Spitzer data (2011 only, open circle; the CoRoT data was only shifted to the mean of the 4.5 μm data). **Right.** CFHT light curves in u (bottom) and r (top) bands.

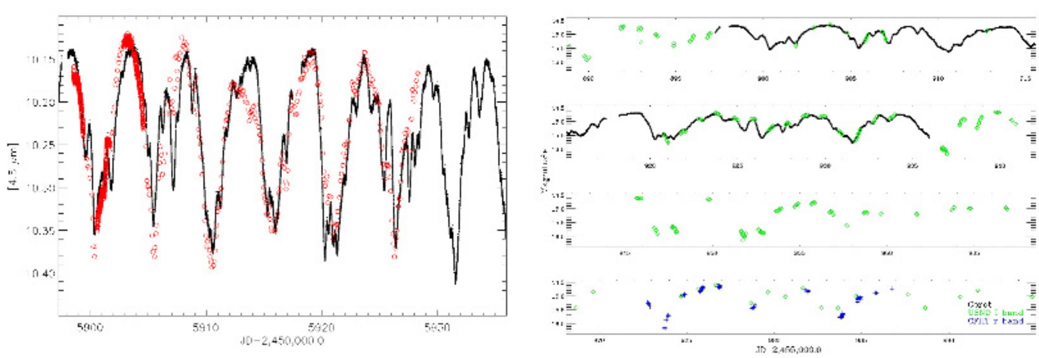

Figure 2. Left. CoRoT light curve (dots) fitted to the 4.5 μm Spitzer data (open circle), assuming a constant extinction ratio of $A_{4.5\mu m}/A_V = 0.25$. **Right.** Combined light curve of CoRoT (dots), CFHT r band (plus sign) and USNO I band (open diamond).

value is very close to the periods obtained from the 2008 Corot light curve, (5.26 ± 0.50) days, and by Lamm et al. [10], (5.22 ± 0.87) days, showing that the main cause of the photometric variability is stable over a few years.

2.2 Spectroscopy

We studied the Hα normalized flux periodicity through a periodogram analysis [11] of the observed time series, done independently in each velocity bin of 0.5 km/s width across the line profile. We notice that the Hα emission profile changes according to the photometric period (figure 3, left), showing that the same phenomenon causes both modulations. In order to investigate this possible correlation between the light curve modulation and spectral variability, we analysed the Hα profiles ordered by position in rotational phase. In the magnetospheric accretion scenario, when the accretion flow is projected onto the stellar photosphere on our line of sight, we expect a more pronounced redshifted absorption, at high velocities. During the 2008 campaign, we observed this feature in the Hα profile

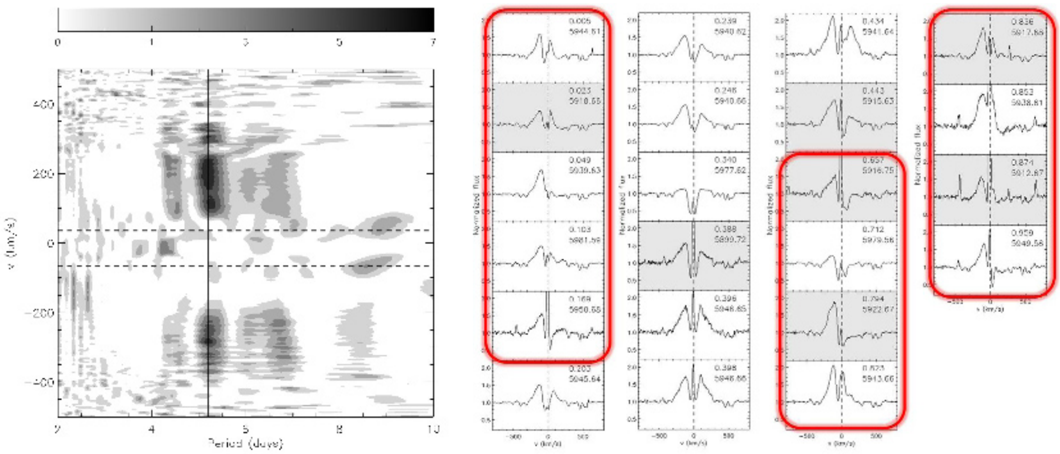

Figure 3. Left. Bidimensional periodogram of the Hα line flux. The horizontal dashed lines delimit the region dominated by nebular emission. The vertical solid line marks the period of 5.21 days. **Right.** Hα profiles ordered by position in rotational phase (upper panel number). The grey background identify the spectra obtained simultaneously with CoRoT. The rectangles highlight the spectra with redshifted absorption.

located in the photometric minimum, revealing a direct connection between the accretion flow and the decreasing of stellar brightness (Fonseca et al. in preparation). In the 2011 campaign, we observe that the spectra with evidence for redshifted absorption are located outside the photometric minima (figure 3, right). Then, the relation observed in 2008 seems not to exist anymore, or to be affected by a time lag.

2.3 Occultation model

According to magnetohydrodynamic (MHD) simultations [12], a small misalignment between the magnetic and rotation axis distorts the inner part of the disk, creating a warp. As V354 Mon is viewed at high inclination (~ 75°), the warp could eclipse periodically part of the stellar photosphere as the system rotates. A model of occultation by circumstellar material [5], originally developed for AA Tau, was applied to the photometric data in order to determine the general parameters of the obscuring material during both observational campaigns. The warp, located at the corotation radius, presented a maximum scale height h/r_c of 0.30 (2008) and 0.33 (2011), and an azimuthal extension of 360°(2008) and 320°(2011) (figure 4, top). These characteristics are very similar to the ones obtained in the model of the variability of AA Tau [5].

The deformation in the disk of V354 Mon seems to change its shape at each rotational cycle, revealing a dynamical interaction between the stellar magnetosphere and the inner part of the disk [13]. Nevertheless, the parameters obtained from the individual fit of the model to the light curve minima are not very different from cycle to cycle (figure 4, bottom, and table 1), indicating that the warp is a permanent structure. Indeed, comparing the parameters of the obscuring material during the two observational campaigns, we notice that this structure remained stable on a timescale of a few years.

As discussed in Subsect. 2.2, the fact that the spectra with redshifted absorption are not located in the photometric minima indicates that the warp that eclipses the star and the funnel flow positions do not coincide, contrary to what was observed in the 2008 campaign. Recent MHD simultations of

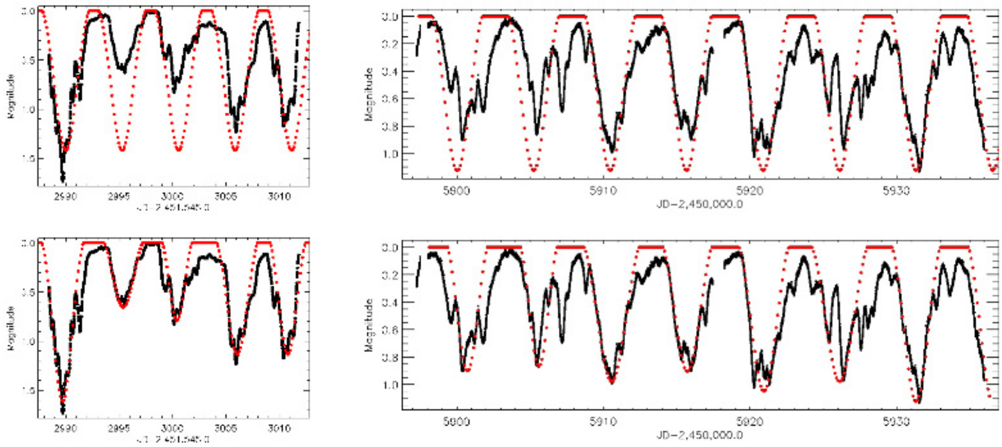

Figure 4. Left. Best fit of the occultation model with fixed parameters (top) and individual fit of light curve minima (bottom) of CoRoT 2008. **Right.** Same as left figure, but for 2011.

Table 1. Occultation model parameters from individual fit of light curve minima

$$h(\phi) = h_{max} \left| \cos \frac{\pi(\phi - \phi_0)}{2\phi_c} \right|$$

	2008		2011	
Minimum	h_{max} (r_c)	$2\phi_c$ (°)	h_{max} (r_c)	$2\phi_c$ (°)
1^o	0.31	320	0.31	260
2^o	0.23	320	0.30	240
3^o	0.25	240	0.31	360
4^o	0.28	320	0.31	320
5^o	0.28	280	0.32	320
6^o			0.31	360
7^o			0.33	310

waves excited in the disk by a rotating tilted dipole [14] have shown that, depending on the system configuration, the warp corotates with the star and its magnetosphere or rotates more slowly, thus leading to a phase shift between the warp and the funnel. The latter could be the case of V354 Mon on 2011.

3 Conclusions

From simultaneous, multiwavelength photometric and spectroscopy observations, we analysed and discussed the characteristics of V354 Mon, a CTTS member of NGC 2264. This star shows a periodic brightness variation, with minima that vary in depth and width every rotational cycle. The Hα profile of this object changes according to the period of photometric modulation, indicating that both are produced by the same phenomenon. As the system is viewed at high inclination, we conclude that a warp in the inner part of the disk is the origin of the observed variations. This warp is likely produced by the dynamical interaction between the circumstellar disk and the stellar magnetosphere inclined with respect to the rotation axis, as also observed in the CTTS AA Tau, and predicted by MHD simulations. We applied a model of occultation by a disk warp to the light curves in two different campaigns, and, comparing the parameters obtained, we notice that the structure remained stable on a timescale of a few years. The similarity between the optical and infrared photometric modulations indicates that both may be caused by the disk warp, but the discrepancy in the amplitude of variation would point to a disk dust processed or different from the interstellar medium dust.

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References

[1] F. Shu, J. Najita, E. Ostriker, F. Wilkin, S. Ruden, S. Lizano, ApJ**429**, 781 (1994)
[2] L. Hartmann, R. Hewett, N. Calvet, ApJ**426**, 669 (1994)
[3] J. Muzerolle, N. Calvet, L. Hartmann, ApJ**550**, 944 (2001)
[4] G.H.R.A. Lima, S.H.P. Alencar, N. Calvet, L. Hartmann, J. Muzerolle, A&A**522**, 104 (2010), `1007.3976`
[5] J. Bouvier, A. Chelli, S. Allain, L. Carrasco, R. Costero, I. Cruz-Gonzalez, C. Dougados, M. Fernández, E.L. Martín, F. Ménard et al., A&A**349**, 619 (1999)
[6] J. Bouvier, K.N. Grankin, S.H.P. Alencar, C. Dougados, M. Fernández, G. Basri, C. Batalha, E. Guenther, M.A. Ibrahimov, T.Y. Magakian et al., A&A**409**, 169 (2003), `arXiv:astro-ph/0306551`
[7] J. Bouvier, S.H.P. Alencar, T. Boutelier, C. Dougados, Z. Balog, K. Grankin, S.T. Hodgkin, M.A. Ibrahimov, M. Kun, T.Y. Magakian et al., A&A**463**, 1017 (2007), `arXiv:astro-ph/0611787`
[8] S.H.P. Alencar, P.S. Teixeira, M.M. Guimarães, P.T. McGinnis, J.F. Gameiro, J. Bouvier, S. Aigrain, E. Flaccomio, F. Favata, A&A**519**, 88 (2010), `1005.4384`
[9] R. Indebetouw, J.S. Mathis, B.L. Babler, M.R. Meade, C. Watson, B.A. Whitney, M.J. Wolff, M.G. Wolfire, M. Cohen, T.M. Bania et al., ApJ**619**, 931 (2005), `arXiv:astro-ph/0406403`
[10] M.H. Lamm, C.A.L. Bailer-Jones, R. Mundt, W. Herbst, A. Scholz, A&A**417**, 557 (2004), `arXiv:astro-ph/0402188`
[11] J.D. Scargle, ApJ**263**, 835 (1982)
[12] M.M. Romanova, G.V. Ustyugova, A.V. Koldoba, R.V.E. Lovelace, ApJ**610**, 920 (2004), `arXiv:astro-ph/0404496`
[13] A.P. Goodson, R.M. Winglee, ApJ**524**, 159 (1999)
[14] M.M. Romanova, G.V. Ustyugova, A.V. Koldoba, R.V.E. Lovelace, MNRAS**430**, 699 (2013), `1209.1161`