Analysis of Star-Disk Interaction in Young Stellar Systems

Nathalia N. J. Fonseca[1], Silvia H. P. Alencar[1], Jérôme Bouvier[2]

[1]UFMG - Brazil (nath@fisica.ufmg.br)

[2]IPAG - France

Abstract

We present 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/FLAMES 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 correlation 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. We also studied V422 Mon, a classical T Tauri star with photometric variations similar to those of V354 Mon at optical wavelengths, but with a distinct behavior in the infrared. The mechanism that produces such difference is investigated, testing the predictions of magnetospheric accretion models.

1 Classical T Tauri stars

Classical T Tauri stars (CTTSs) are young ($\sim$ 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 present:

- strong magnetic fields ($\sim$ few kG);
- photometric and spectroscopic irregular variability;
- strong Hα emission, with redshifted and blueshifted absorptions;
- forbidden emission lines ([OI], [SII], and [NII]);
- emission excess with respect to the stellar photosphere at wavelengths from X-rays to radio.

These general features are explained by magnetospheric accretion models (Shu et al., 1994; Hartmann et al., 1994; Muzerolle et al., 2001; Lima et al., 2010), in which a young star accretes material from a circumstellar disk (Figure 1). The disk is disrupted at a few stellar radii by strong magnetic stellar field and the gas from the inner disk is channeled on to the stellar surface along the field lines, creating accretion funnels. Hot spots are produced in the photosphere by the shock of material at free fall velocity. Material is also ejected from the system as a disk wind.

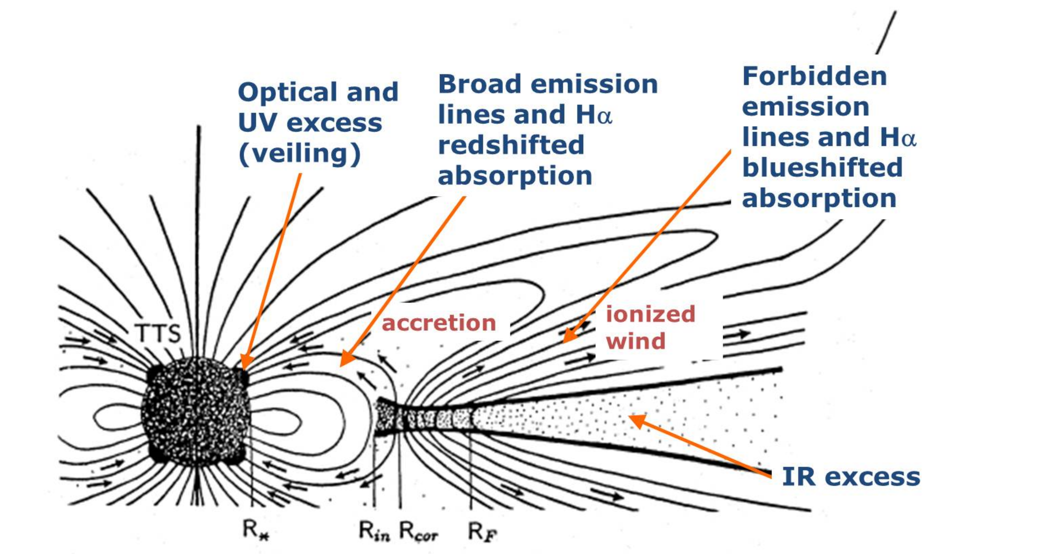


Figure 1. Illustration of the interaction between the stellar magnetosphere and the accretion disk in CTTSs. The predictions of each model about the observed characteristics are identified. Adapted from Paatz & Camenzind (1996).

2 Coordinated Synoptic Investigation of NGC 2264 (CSI NGC 2264)

From December 2011 to January 2012, an international campaign was organized to observe the young stellar cluster NGC 2264 simultaneously with:

- CoRoT for 39 days (optical);
- Spitzer for 29 days (infrared);
- Chandra for 300 ks (3.5 days) (X-rays);
- VLT/FLAMES for 40h (20 nights) (spectroscopy);
- CFHT/Megacam for 15 nights (*ur* bands) in Feb. 2012;
- USNO for $\sim$ 70 nights (I band) from Nov. 2011 to Mar. 2012;
- other ground-based telescopes.

3 V354 Mon

V354 Mon is a CTTS member of NGC 2264, also present in a previous aditional program of CoRoT, in which the satellite observed continuously the young cluster for 23 days in March 2008. For V354 Mon (K4V), simultaneous échelle spectroscopy was obtained with the SOPHIE spectrograph at the Observatoire de Haute Provence (CNRS, France).

3.1 CoRoT photometry

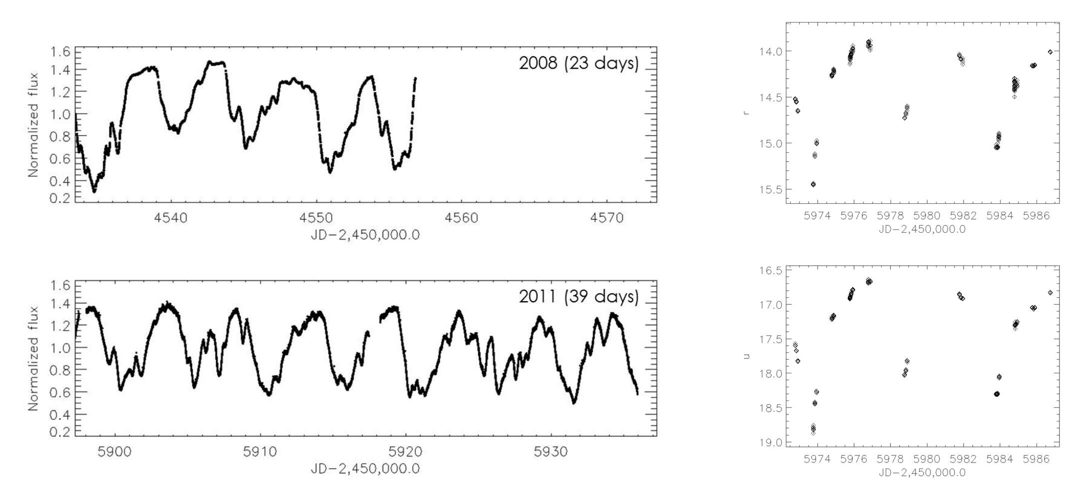


Figure 2. **Left** CoRoT light curves obtained in 2008 (top) and 2011 (bottom). **Right** CFHT light curves in *u* (bottom) and *r* (top) bands.

The star light curves in the two campaigns show the same morphological characteristics, with minima that vary in depth and width every rotational cycle (Figure 2, left).

3.2 CFHT/Megacam photometry

V354 Mon exhibits simultaneous eclipses in *u* and *r* bands (Figure 2, right), but with a larger amplitude in *u* (2.23 $\pm$ 0.01) than in *r* (1.57 $\pm$ 0.01). No UV excess emission was measured, indicating that the hot spot may be eclipsed most of the time by the accretion flow.

3.3 CoRoT + CFHT + USNO photometry

Combining the Corot, CFHT, and USNO datasets (Figure 3, left), we have a photometric coverage for more than 100 days, which enabled a good determination of the period, (5.21 $\pm$ 0.04) days (Figure 3, right). This value is very close to the periods obtained from the 2008 Corot light curve, (5.26 $\pm$ 0.50) days, and by Lamm et al. (2005), (5.22 $\pm$ 0.87) days, showing that the main cause of the photometric variability is very stable over a few years.

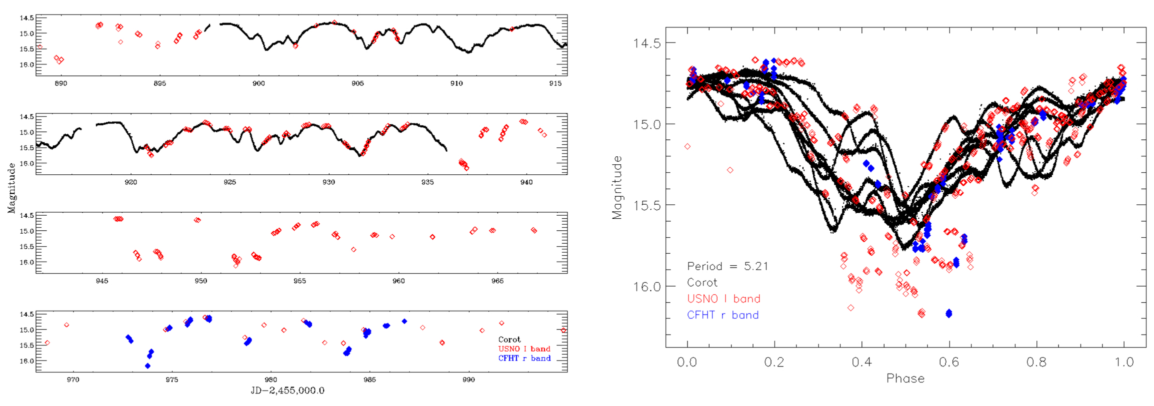


Figure 3. **Left** Combined light curve of CoRoT (black), CFHT *r* band (blue) and USNO I band (red). **Right** Combined light curve folded in phase with the period of 5.21 days.

3.4 CoRoT + Spitzer photometry

The photometric modulation in the infrared is very similar to the optical (Figure 4, 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 changes, 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 4, right). This value is 5 times higher than the expected for extinction by interstellar dust (Indebetouw et al., 2005), which would indicate that the dust grains in the disk are larger than in the interstellar medium.

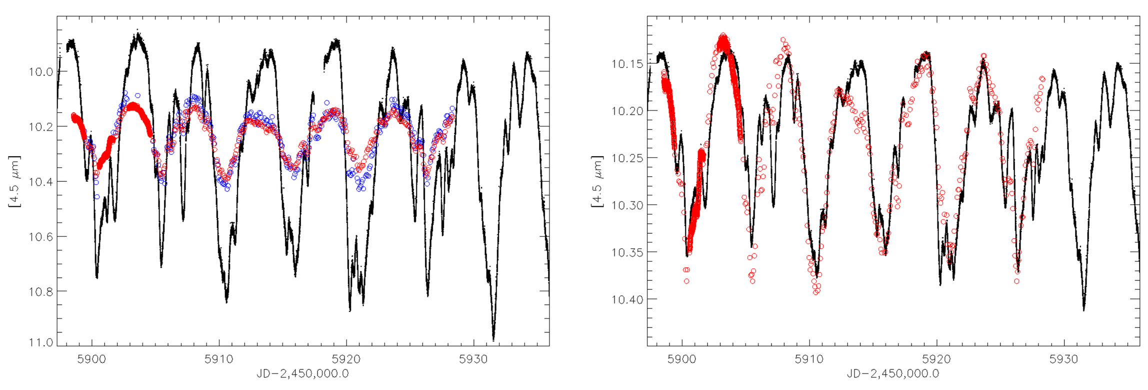


Figure 4. **Left** Comparison between the light curves of V354 Mon in the optical (black) and in the infrared (blue for 3.6 μm, red for 4.5 μm). **Right** CoRoT light curve fitted to the 4.5 μm Spitzer data, assuming a constant extinction ratio.

3.5 VLT/Flames spectroscopy

We studied the Hα normalized flux periodicity through a periodogram analysis (Scargle, 1982) of the observed time series, done independently in each velocity bin of 0.5 km/s along the profile. We notice that the Hα emission profile changes according to the photometric period (Figure 5), showing that the same phenomenon causes both modulations.

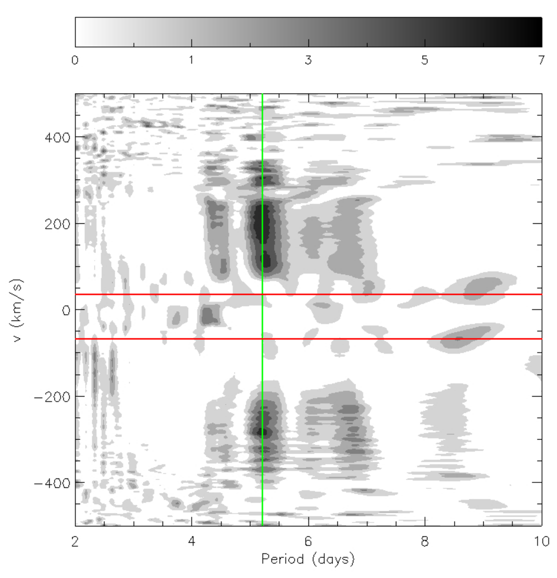


Figure 5. Bidimensional periodogram of the Hα line flux. The red thick lines delimit the region dominated by nebular emission. The green thick line marks the period of 5.21 days.

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 (Figure 6, left). We observe that the spectra with evidence of redshifted absorption are located outside the photometric minima. In the magnetospheric accretion scenario, when the accretion flow is projected on the stellar photosphere in our line of sight, we see a more pronounced redshifted absorption, at high velocities. In the 2008 campaign, we observed this feature in the spectrum located in the photometric minimum (Figure 6, bottom left), revealing a connection between the accretion flow and the decreasing of stellar brightness. But in the new campaign, this relation seems to not exist anymore.

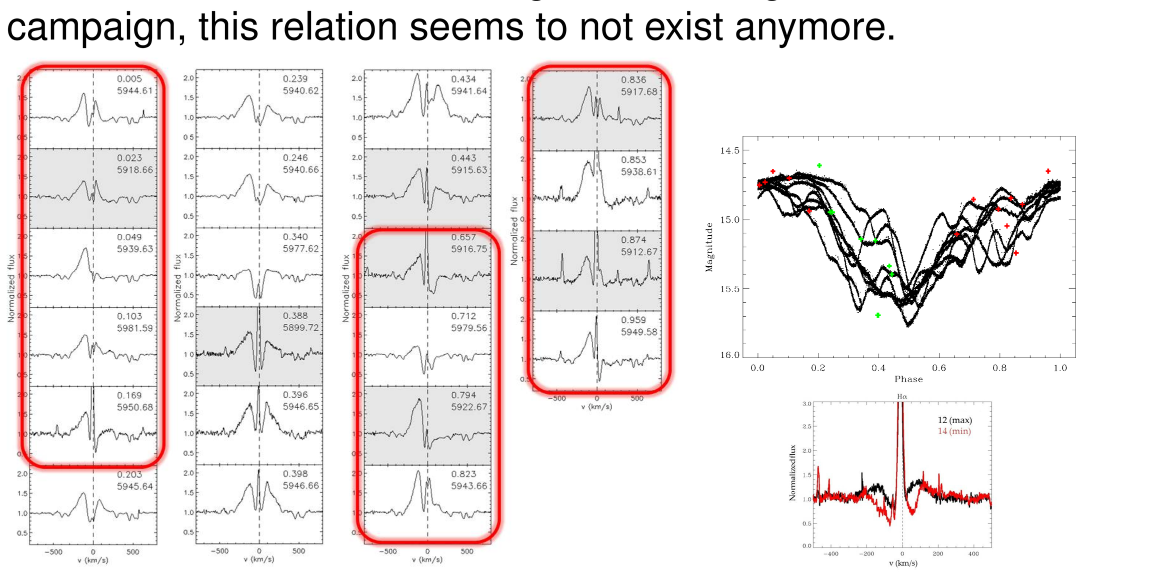
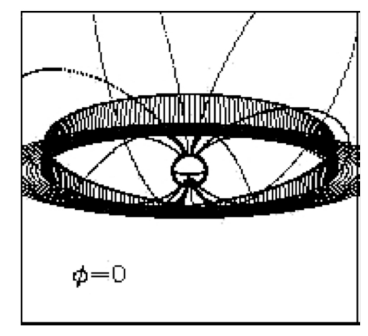


Figure 6. **Left** Hα profiles ordered by position in rotational phase (middle panel number). The grey background identify the spectra obtained simultaneously with CoRoT. The red rectangles highlight the spectra with redshifted absorption. **Right** CoRoT light curve folded in phase to locate the spectral observations (plus signs) (top). Comparison between the Hα profile observed in the 2008 campaign, corresponding to a photometric maximum (black) and a minimum (red) (bottom).

3.6 Occultation model

According to magnetohydrodynamic (MHD) simultations (Romanova at al., 2004), the small misalignment between the magnetic and rotation axis observed in V354 Mon distorts the inner part of the disk, creating a warp. As this system is viewed at high inclination ($\sim$ 75°), the warp could eclipse periodically part of the stellar photosphere as the system rotates. A model of occultation by circumstellar material (Bouvier et al., 1999), shown in Figure 7, 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 of 0.30 (2008) and 0.33 (2011), and an azimuthal extension of 360°(2008) and 320°(2011) (Figure 8, top). These characteristics are very similar to the ones obtained in the fit of the model to the variability of the CTTS AA Tau (Bouvier et al., 1999).



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

$$r_c = \left(\frac{P}{2\pi}\right)^{2/3} (GM_*)^{1/3}$$

Figure 7. **Left** A system with a deformation in the inner part of the disk, according to the occultation model (Bouvier et al., 1999). **Right** Equation describing how the height of the inner disk varies with the azimuthal position in the disk. The warp is located at the corotation radius r_c.

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 (Goodson & Winglee, 1999). Nevertheless, the parameters obtained from the individual fit of the model to the light curves minima are not very different (Figure 8, 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.

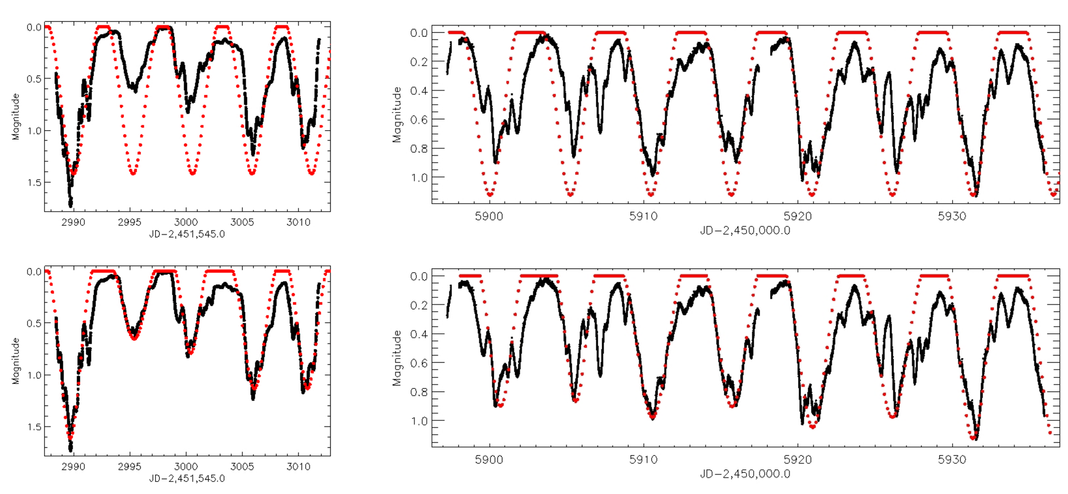


Figure 8. **Left** Best fit of the occultation model (top) and individual fit of light curve minima (bottom) of CoRoT 2008. **Right** Same as left figure, but for CoRoT 2011.

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

	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

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 simulations of waves in the disk excited by a rotating tilted dipole (Romanova et al., 2013) 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.

4 V422 Mon

V422 Mon is a CTTS that presents light curve minima that vary in depth and width every rotational cycle (Figure 9, left), with a period of (8.93 $\pm$ 0.92) days. This similarity with V354 Mon would indicate that both present a similar geometry. But as we can observe in Figure 9 (right), there is no agreement between the optical and infrared photometric variations of V422 Mon. The optical modulation may be produced by a warp in the inner disk, as in V354 Mon, but the infrared variation may be caused by changes in the disk emission.

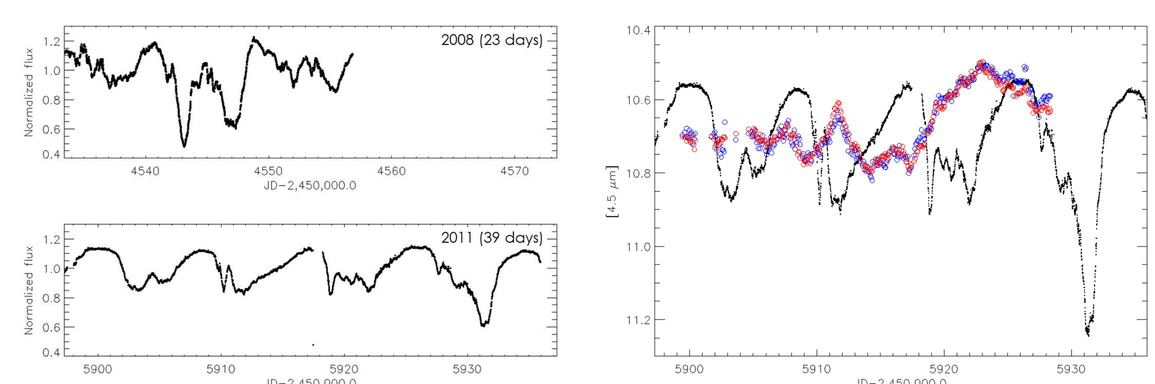


Figure 9. **Left** CoRoT light curves obtained in 2008 (top) and 2011 (bottom). **Right** Comparison between the light curves of V422 Mon in the optical (black) and in the infrared (blue for 3.6 μm, red for 4.5 μm).

Acknowledgments

CNPq CAPES CNRS

References

- Bouvier, J., Chelli, A., Allain, S., et al. 1999, A&A, 349, 619
- Goodson, A. P. & Winglee, R. M. 1999, ApJ, 524, 159
- Hartmann, L., Hewett, R., & Calvet, N. 1994, ApJ, 426, 669
- Indebetouw, R., Mathis, J. S., Babler, B. L., et al. 2005, ApJ, 619, 931
- Lamm, M. H., Mundt, R., Bailer-Jones, C. A. L. & Herbst, W. 2005, A&A, 430, 1005
- Lima, G. H. R. A., Alencar, S. H. P., Calvet, N., Hartmann, L., & Muzerolle, J. 2010, A&A, 522, 104
- Muzerolle, J., Calvet, N. & Hartmann, L. 2001, ApJ, 550, 944
- Paatz, G. & Camenzind, M. 1996, A&A, 308, 77
- Romanova, M. M., Ustyugova, G. V., Koldoba, A. V. & Lovelace, R. V. E. 2004, ApJ, 610, 920
- Romanova, M. M., Ustyugova, G. V., Koldoba, A. V. & Lovelace, R. V. E. 2013, MNRAS, 430, 699
- Scargle, J. D. 1982, ApJ, 263, 835
- Shu, F., Najita, J., Ostriker, E., et al. 1994, ApJ, 429, 781