The Extension of the Corona in Classical T Tauri Stars

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Abstract. The extension of the corona of classical T Tauri stars (cTTS) is under discussion in the Astrophysical community. The standard model of magnetic configuration of cTTS predicts that coronal magnetic flux tubes connect the stellar atmosphere to the inner region of the disk. Gas accretion from the disk to the star takes place along those magnetic tubes. Flaring events have been detected in cTTS. The weakest flares are assumed to have their origin in solar-like magnetic loops. However, strong, long-duration flares may be related to those long structures connecting the star and the disk. Such scenario is supported by some past result based on the use of hydrodynamic models with the assumption that those strong flares take place in single or small groups of loops. This assumption is still controversial. To disentangle this controversy, new independent measurement of the loop length are needed. We present an approach for determining the length of flaring loops based on the quasi-periodic MHD oscillations of loop emission after strong flares.

1. Model for magnetic tube oscillations

A longitudinal wave that propagates along a tube of length L with a velocity c_t (tube velocity) shows a period P such that $P = 2L/c_\mathrm{t}$. In the magnetohydrodynamic (MHD) approximation, the tube velocity satisfies the relation

$$\frac{1}{c_\mathrm{t}^2} = \frac{1}{c_\mathrm{s}^2} + \frac{1}{c_\mathrm{A}^2} \tag{1}$$

where $c_\mathrm{A} = B/(4\pi n_i m_i)^{1/2}$ (in the c.g.s.) is the Alfvén velocity and $c_\mathrm{s} = (2\gamma k_\mathrm{B} T/m_p)^{1/2}$ is the sound velocity for an ideal gas. Here, n_i and m_i are, respectively, the ion number density and the ion mass and B is the magnetic field strength. In the sound velocity equation, γ is the adiabatic index, m_p is the proton mass (assuming total ionization for the gas), $k_{\rm B}$ is the Boltzmann constant and T is the plasma temperature.

MHD oscillations may be caused by different processes, including spontaneous reconnection (e.g. Nakariakov et al. 2010). A particularly interesting process is that proposed by Zaitsev & Stepanov (1989). According to the authors, the evaporation of chromospheric material during the flare produces a centrifugal force that causes, alternatively, stretch and contraction of the magnetic tube and triggers Alfvén oscillations of the magnetic flux tube that are damped. The relative amplitude of the oscillation follows the relation for slow magnetoacustic waves

$$\frac{\Delta I}{I} = \frac{4\pi n T}{B^2} \tag{2}$$

being n the plasma density, T its temperature, B the magnetic field strength, I the oscillation intensity and $\Delta I/I = \Delta B/B$.

The existence of a relation between the magnetic field and the relative amplitude of the oscillation permits to determine the strength of the magnetic field at the top of the coronal loop by measuring the damping of the intensity of the oscillation and the parameters of the plasma (temperature and density). This approach was applied by Mitra-Kraev et al. (2005) for the oscillations observed in an X-ray flare of the M dwarf AT Mic, obtaining $B \sim 100$ G and a loop length $L \sim 10^{10}$ cm, consistent with the value obtained assuming radiative cooling and pressure balance (Shibata & Yokoyama 2002). Recently, Pillitteri et al. (2014) used the same model to determine the length of a flaring loop in the hot-jupiter host star HD 189733. The authors obtained a length of $\sim 2-4$ R$_\star$, suggesting the probable interaction between the star and the planet.

In a purely hydrodynamic (HD) scenario, the warming of the chromosphere at the loop base is very brief and the loop is not completely filled up with hot material. Blobs of hot dense material ascend along the tube at supersonic velocities ($v > c_{\rm t}$) from both sides of the loop until they encounter at the top and descend again. The process is periodic until final dissipation and produces oscillations in density detected in HD modeling. In this case, there is no way to determine the length of the flaring loop, but a lower limit can be determined assuming the wave is propagating at the velocity of sound in the tube ($v = c_{\rm t}$).

2. Application to cTTS in Orion

Figure .1 shows oscillations detected in the X-ray band in some classical T Tauri stars (cTTS) in the Orion Nebula Cluster (ONC). Light curves are from the COUP (Favata et al. 2005). Rapidly damped slow oscillations are observed in each case. Table .1 lists results on the loop lengths determined by using Zaitsev & Stepanov (1989)'s method. Our results are compared to those obtained by Favata et al. (2005) from HD modeling (Reale et al. 2004). The observed similarity with results from Favata et al. (2005) suggests that the oscillations are related to Alfvén waves propagating along the reconnected tube.

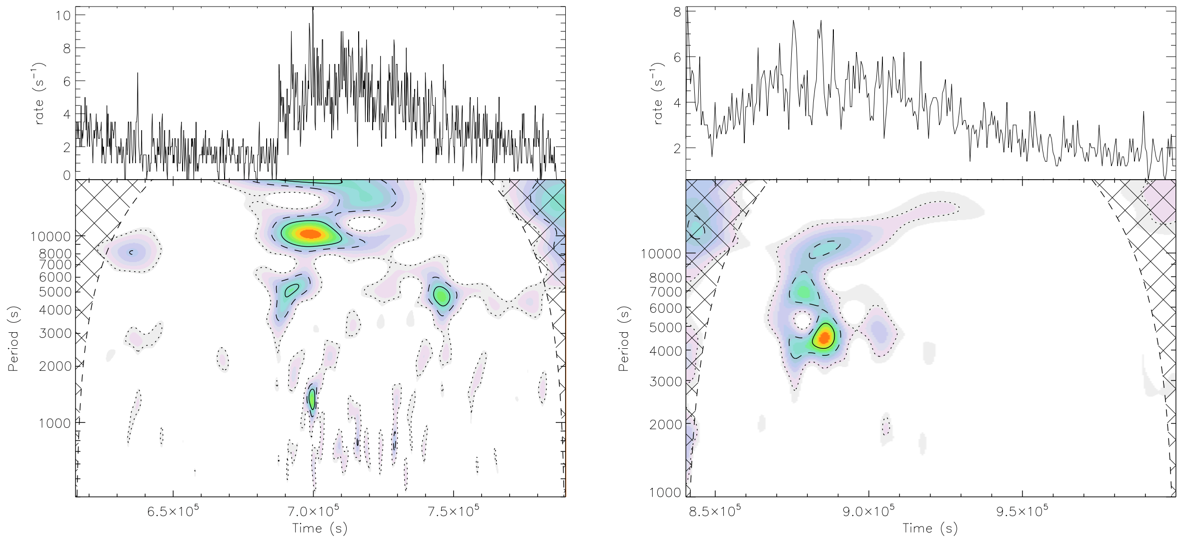

Figure .1: Two examples of oscillations detected in some cTTS in the ONC (Favata et al. 2005). In both cases, oscillations occur at the top of the rise phase of the flare's light curve, but the period of the oscillation differs.

Table .1: Results of applying the Zaitsev & Stepanov (1989)'s model to several cTTS in the COUP sample (Favata et al. 2005).

	Favata et al. (2005)			This work	
ID	$T_{\rm peak}$ (MK)	L (10^{10} cm)	$L/R_\star$	L (10^{10} cm)	$L/R_\star$
43	142	112 (75 - 134)	5.5	100.0	5.0
597	87	22 (0 - 75)	1.6	26.0	1.9
976	270	76 (...)	12.0	30.0	4.7
1608	258	82 (0 - 99)	6.7	108	9.0

3. Discussion and conclusions

By using the simple model of Zaitsev & Stepanov (1989) for explaining the appearance of oscillations in reconnected magnetic loops in cTTS, we determined loop lengths for those stars that are in agreement with the results obtained by Favata et al. (2005) from hydrodynamic modeling. In their work, Favata et al. (2005) assumed that the observed flare light curves come from the ignition of a single loop, according to Reale et al. (2004). This approach is quite controversial and many authors disagree with it and prefer to use scalling laws to determine the parameters of the flaring loop (e.g. Aschwanden et al. 2008). The assumption of the single loop scenario yields to long loops in strong flaring events, with magnetic field strengths similar to those found in similar loops in the Sun. Instead, the use of scaling laws leads to determining shorter loop lengths and stronger magnetic fields. To disentangle this dichotomy is important in the case of cTTS, in order to validate or disprove the canonical scenario of the interaction between star and disk (Camenzind 1990). The use of an independent method to measure the length of the reconnecting magnetic loops can deeply improve in the knowledge of the structure of the corona of cTTS. In particular, analyzing oscillations like the ones studied in this work we will be able to determine parameters from flaring loops and compare results with those obtained by different methods.

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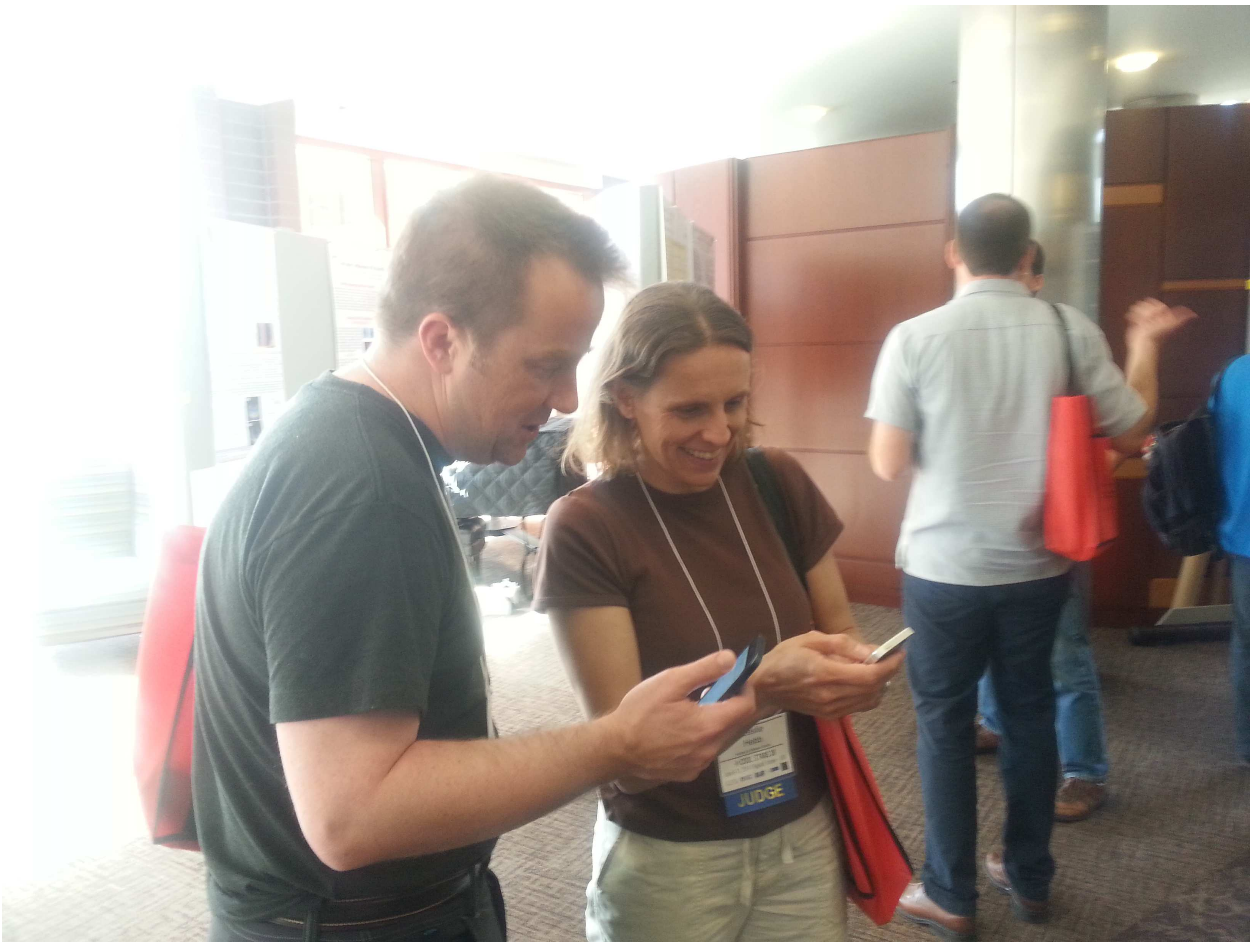

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