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Effects of intense flaring activity on accretion disk of Classical T Tauri Stars

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Abstract. Classical T Tauri stars (CTTSs) are young low-mass stellar objects that accrete mass from their circumstellar disks characterized by high levels of coronal activity. Here, we investigate, using a 3D MHD model, if an intense coronal activity due to flares that occur close to the accretion disk may perturb the stability of the inner disk triggering accretion episodes. We observe the formation of several loops that link the star to the disk; all these loops build up a hot extended corona with an X-ray luminosity comparable with typical values observed in CTTSs. We found that the intense flaring activity close to the disk can strongly perturb the disk stability, in fact accretion funnels may be triggered by the flaring activity and thus contribute to the mass accretion rate of the star.

1. Introduction

Classical T Tauri stars (CTTSs) are young stars surrounded by an accretion disk from which they interact through accretion process. The accretion process plays an important role in the early phase of stellar formation, in fact it regulates the changes of mass and angular momentum between the star and the disk. Despite the important role of the accretion phenomena to understand the physics of stellar formation, there are some point not fully understood. One of the most important issue is how the material loses angular momentum and moves from the outer region of the disk to the inner disk and eventually falls down into the star. It is believed that the turbulences in the disk are the responsible for the required angular momentum losses (Shakura and Sunyaev 1973). These turbulences are triggered by magneto-rotational instabilities (MRI, Balbus and Hawley 1991, 1998). However MRI alone may not explain the amount of angular momentum removed from the system (King et al. 2007; Fromang and Papaloizou 2007; Shi et al. 2016). On the other hands, CTTSs radiate strongly in X-ray. This emission comes from the heated plasma in the outer part of the stellar corona with temperature from 1 to 100 MK. The responsible for the plasma heating is the strong magnetic activity in the stellar corona. In fact, the effects of this strong magnetic field activity are high energetic flares that are generated from a quick release of energy in the disk surface. Orlando et al. (2011) proved that a single bright flares produces an hot magnetic loop that links the star to the disk. Moreover the disk is strongly perturbed by the flare. Part of the disk material in proximity of the flare evaporates and an overpressure wave, originated by the flare, propagates through the disk. When the overpressure waves reaches the opposite side of the disk, the disk material is pushed away from the equilibrium position, and is channeled by the magnetic field, forming an accretion column.

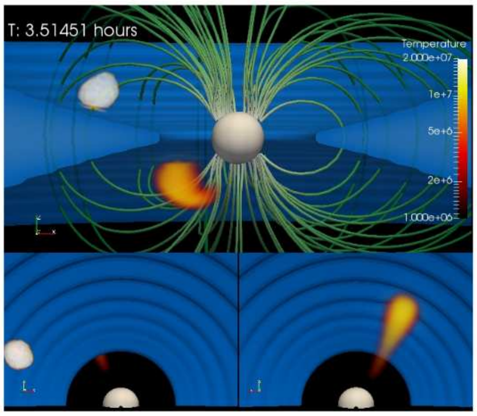
The task of this research is to investigate the stability of a circumstellar disk subject to the continuous perturbation of a storm of flares of small-to-medium intensity, and to test the idea that the flaring activity commonly observed in low-mass pre-main-sequence stars can be an efficient mechanism to trigger accretion onto the protostar itself and, possibly, to generate outflows. Flaring activity may, thus, turn out to be an important factor in the exchange of angular momentum and mass within the system.

2. The model

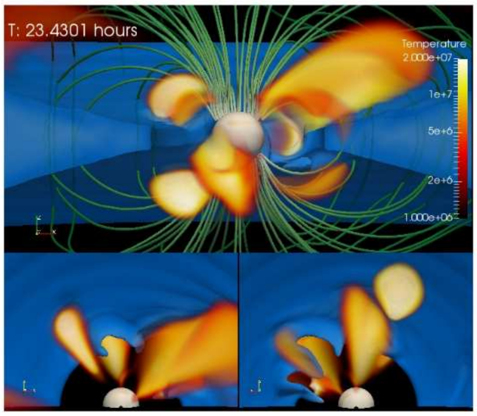
We developed a set of 3D MHD simulations, describing a rotating magnetized star surrounded by a thick Keplerian disk perturbed by a storm of small-to-medium flares. The flares occur in the inner portion of the disk, below the co-rotation radius, where accretion streams are believed to originate. We used the already tested setup developed, using the PLUTO code, by Orlando et al. (2011). The setup consist of a star of mass $M^* = 0.8$ Msun and radius $R^* = 2$ Rsun located at the origin of a 3D spherical coordinate system. The rotation period of the star is assumed to be 9.2 days. The initial unperturbed stellar atmosphere is approximately in equilibrium and consists of three components: the stellar magnetosphere, the extended stellar corona, and the Keplerian disk. Initially, the magnetosphere is assumed to be force-free, with dipole and an octupole topology, the first prevails away from the star, the latter close to the star. Magnetic moments are aligned with the rotation axis and chosen to have a magnetic field strength of the order of 1 kG at the stellar surface. The initial corona and disk are set to satisfy mechanical equilibrium involving centrifugal force, gravity and pressure. The distribution of density and pressure is barotropic and depend (together with angular velocity) only on the radius. The isothermal disk is cold, dense and rotates with angular velocity close to the Keplerian value; its rotation axis is aligned with the magnetic moment. The disk is initially truncated by the stellar magnetosphere at the radius Rd where the ram pressure of the disk is equal to the magnetic pressure; for the adopted parameters, $Rd = 2.86R^*$ and the co-rotation radius will be located at $Rco = 9.2R^*$. The corona is initially isothermal with temperature $T = 4MK$ and at low density. The corona initially rotates with angular velocity equal to the Keplerian rotation rate of the disk to have approximately equilibrium conditions. The simulation domain in 3D spherical coordinates extends from the radial coordinate $r = R^*$ to $r = 15$ R*; the angular coordinates theta and phi range between 0 and 180 degrees. The angular coordinates theta and phi are discretized with 128 points. The radial coordinate is discretized with 128 points on a logarithmic grid with the mesh size increasing with the coordinate. Free flow conditions are assumed at the inner and outer radial boundaries and in the boundary conditions at the rotation axis ($\theta = 5$ and $\theta = 174$), and periodic conditions at the two other boundaries. The simulations last five days of physical time to allow the formation of several accretion columns induced by the flares.

3. Results and conclusions

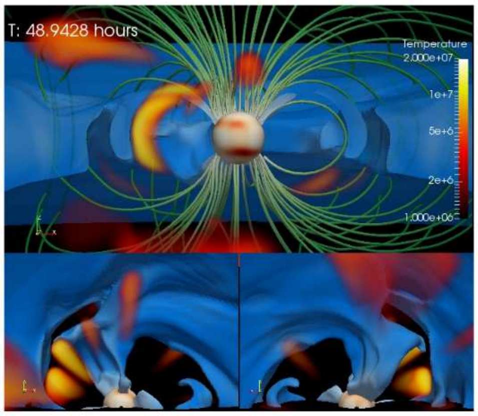
The results of our work are showed in Fig. 1. The first flare explode after 1 hour, of evolution. The heated plasma expands rapidly and form an hot loop that links the disk to the stellar surface. The overpressure waves generated by this flare is not strong enough to produce an accretion column. After the first flare, other flares occur in the disk surface. Each of them produce a significant amount of hot plasma that fills hot loops; all these loops build up a hot extended corona that emits mainly in the UV and X-ray bands with fluxes consistent with those observed. The intense flaring activity close to the disk perturbs the disk stability. In fact, as a re-



(a)



(b)



(c)

Fig. 1. Snapshot of the reference case after 30 hours. Top image edge-on view of the system, bottom left and right pole-on views of the system. In blue the material with density grater than $10^{11} cm^{-3}$, in log scale from red to yellow the volume rendering of temperature. The green lines represent the magnetic field lines.

sult of the flares, a series of overpressure waves travel through the disk, modifying its configuration and stability. Eventually accretion funnels are triggered contributing to the mass accretion rate of the star. Accretion rates synthesized from the simulations are comparable with those inferred from X-ray observations. The results of our work lead to several conclusions. A series of small to medium flares in the disk produces a perturbation strong enough to generate accretion column (Fig. 1). Fig. 2 shows the accretion rates synthesized from the simulations. The accretion rates are comparable with those inferred by X-ray observations (Herczeg and Hillenbrand 2008; Curran et al. 2018). Moreover, the dynamics of the accretion column is affected by the presence of flares and as a result the accretion column are density structured. The hot plasma generated by the flares produces an hot extended corona that irradiates strongly in the UV and X-ray. This may have important consequence in the physical and chemical evolution of the disk.

4. CPU usage

The time-dependent MHD equations are solved numerically, using the PLUTO code Mignone et al. (2007). PLUTO is designed to make efficient use of massively parallel

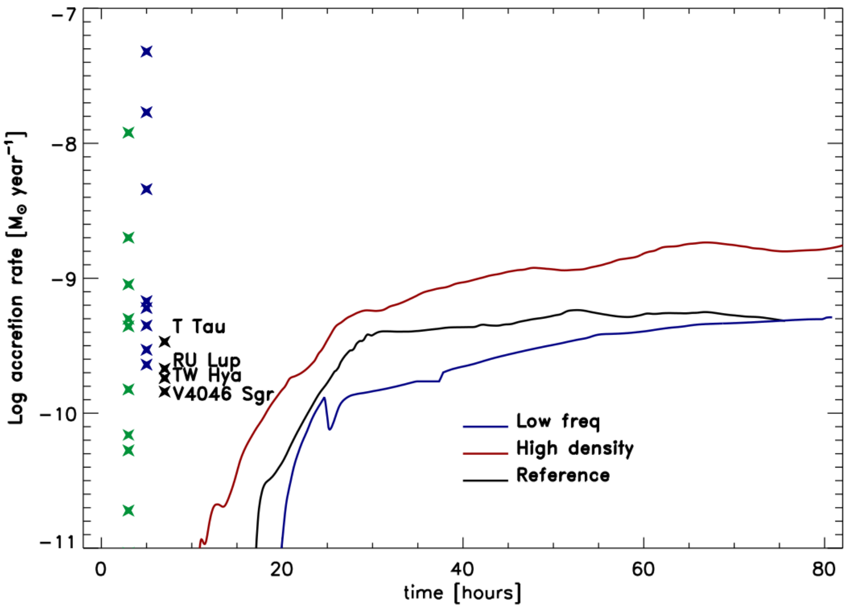


Fig. 2. Evolution in time of accretion rate synthesized from simulations. Black line represents the reference case, the red line the high density case and the blue line the low frequency case. The crosses represent the values of mass accretion rate inferred from optical-near UV observations for a sample of low-mass stars and brown dwarfs (green, Herczeg and Hillenbrand 2008), for a sample of solar-mass young accretors (blue, Herczeg and Hillenbrand 2008), and for an X-ray-selected sample of CTTSs (black, Curran et al. 2018).

computers using the message-passing interface (MPI) for interprocessor communications. Our task for this project was to perform 2 simulation to complete the exploration of paramether space. To achieve our task we asked for 1.000.000 cpu hours on Marconi broadwell. We obtained 500 000 cpu hours on Marconi broadwell and 1.000.000 cpu hours on Marconi Knl.

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