Radiation Magnetohydrodynamic Models and Spectral Signatures of Plasma Flows Accreting onto Classical T Tauri Stars

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1 Introduction

Classical T Tauri Stars (CTTSs) are young stars surrounded by a disk. According to the largely accepted magnetospheric accretion scenario [1], the disk extends internally until the, so called, truncation radius. Here the magnetic field is strong

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enough to dominate the plasma dynamics. The plasma is funneled by the magnetic field to form accretion columns that falls into the star.

Several lines of evidence support this idea, in particular accreting CTTSs show a soft X-ray (0.2–0.8 KeV) excess, with typical lines produced at temperature of 10^5-10^6 K. This has been interpreted as due to the impacts of accreting material onto the stellar surface, at the impact region a shock is produced and dissipates the kinetic energy of the downfalling material, thereby heating up the plasma to temperature of few million degrees, producing X-ray emission [2, 3].

In the last 10 years the explanation of the soft X-ray excess in CTTSs in terms of accretion shocks was well supported by hydrodynamic (HD) and magnetohydrodynamic (MHD) models. Time-dependent one-dimensional (1D) models of radiative accretion shocks in CTTSs provided a first accurate description of the dynamics of the post-shock plasma [4, 5] In particular [5] proposed a 1D HD model of a continuous accretion flow, thus assuming the ratio between the thermal pressure and the magnetic pressure $\beta \ll 1$, impacting the chromosphere of a CTTS. Their model reproduces the main features of high spectral resolution X-ray observations of the CTTS MP Mus. More recently, 2D MHD models of accretion impacts have been studied [6–8]. 2D models allow to explore those cases where the $\beta \ll 1$ approximation cannot be applied and, therefore, the 1D approximation cannot be used. These models proved that the accretion dynamics strongly depends on the configuration and strength of the magnetic field. In particular, the atmosphere around the impact region can be perturbed by the accreting plasma.

All the previous models do not take into account the effects or radiative gains by the matter. The only published work where the radiation effects are considered is by Costa et al. [10]. This model is the first attempt to include the full radiative transfer (RT) effects in the framework of accretion impacts. Costa el al. [10] do not directly couple the RT effects with HD equations, but include them in an iterative way. More precisely they first solve the HD equations, then calculate the heating due to the RT, and then perform the simulation again including the calculated heating. This first approach could still prove that, in certain conditions, the radiation coming from the post-shock region may be absorbed by the unshocked material above in the accretion column. The absorption may heats up the unshocked accretion column at temperature between 10^4-10^6 K.

In this work we propose the first simulation including the radiative transfer effects, in non-LTE regime coupled with the HD equations.

2 The Model

Our model describes an accretion column with uniform density of 10^{11} cm^{-3} impacting onto the chromosphere of a CTTS. The accretion column is assumed to fall along the z-axis with an impact velocity of 500 km/s, and an initial temperature of 2×10^4 K. For the sake of simplicity, we assume plane parallel approximation,

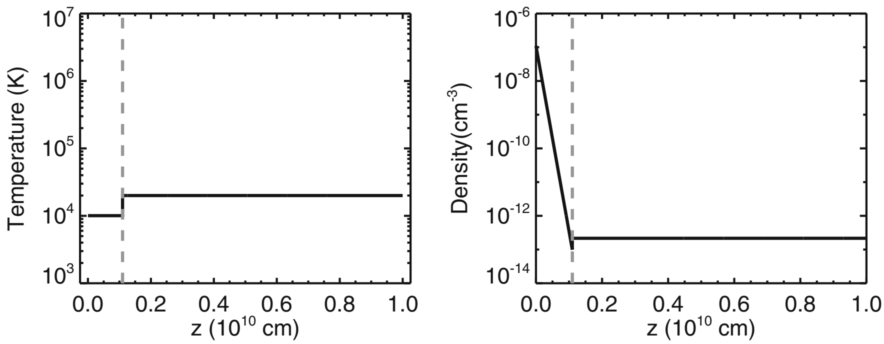

Fig. 1 Initial profiles of temperature (on the left) and density (on the right) for the simulation. The dotted vertical lines indicates the initial position of the chromosphere

and follow the evolution of the internal region of the accretion column. It is the same as assuming that in all the domain $\beta \ll 1$.

Initially, the accretion column, which is unshocked, is placed just above an idealized chromosphere, which is assumed to be at uniform temperature at 10^4 K. Figure 1 shows the initial conditions. The model solves the radiative hydrodynamics (RHD) equations: conservation of mass, momentum, total plasma energy (ϵ) and comoving-frame radiation energy (E), taking into account the gravity from the central star, the thermal conduction and the radiative heating and radiative losses. The total radiative properties (Plank mean opacity k_P, Rosseland mean opacity k_R, and radiative losses L) are calculated in the NLTE regime [12]. The set of RHD equations that we solve, under the flux-limited diffusion approximation, is

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (1)$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u} \times \mathbf{u}) + \nabla p = \rho \mathbf{g} + \frac{\rho k_R}{c} \mathbf{F} \quad (2)$$

$$\frac{\partial \epsilon}{\partial t} + \nabla \cdot [(\epsilon + p)\mathbf{u}] = \rho \mathbf{u} \mathbf{g} + \nabla \cdot F_c - L + k_P \rho c E \quad (3)$$

$$\frac{\partial E}{\partial t} + \nabla \cdot \mathbf{F} = L - k_P \rho c E \quad (4)$$

$$p = \rho \frac{k_B T}{\mu m_H} \qquad \mathbf{F} = -\lambda \frac{c}{k_R \rho} \nabla E \quad (5)$$

where ρ is the density, $\mathbf{u}$ the velocity, p the gas pressure, $\mathbf{g}$ the gravity, F_c the thermal conduction, c the speed of light, $\mathbf{F}$ the comoving-frame radiation flux, and λ the flux limiter. The equation are solved in a Cartesian coordinates system (x,y,z).

The calculation were performed using PLUTO v4.0 [9], a modular, Godunov-type code for astrophysical plasmas. PLUTO was coupled with a RT module, which was originally restrained to the LTE regime [11], and which we have upgraded in order to take into account the NLTE conditions.

The domain consists of a 3D uniform grid with only 3 points for x and y-axes and 8192 points for the z-axis, this grid was chosen as a trade-off between computational cost and spatial resolution.

3 Preliminary Results

This is still work in progress, hence the results presented are preliminary. The evolution of the system is shown in Fig. 2.

Initially, the accretion column is located just above the chromosphere.

The density map (Fig. 2 left) shows that, initially, the accretion column sinks into the chromosphere. It stops when the thermal pressure in the chromosphere equals the ram-pressure of the stream. At this point, a shock propagates through the accretion column forming a post-shock region (light blue in Fig. 2 left and dark red in Fig. 2 right). The post-shock regions has a transient phase (between 100 and 300 s), where the accretion column is still sinking into the chromosphere. During the transient phase the post-shock region extends up to $\approx 5 \times 10^8$ cm above the impact region. After the transition phase the post-shock region increases, reaching a maximum value of $\approx 3 \times 10^9$ cm.

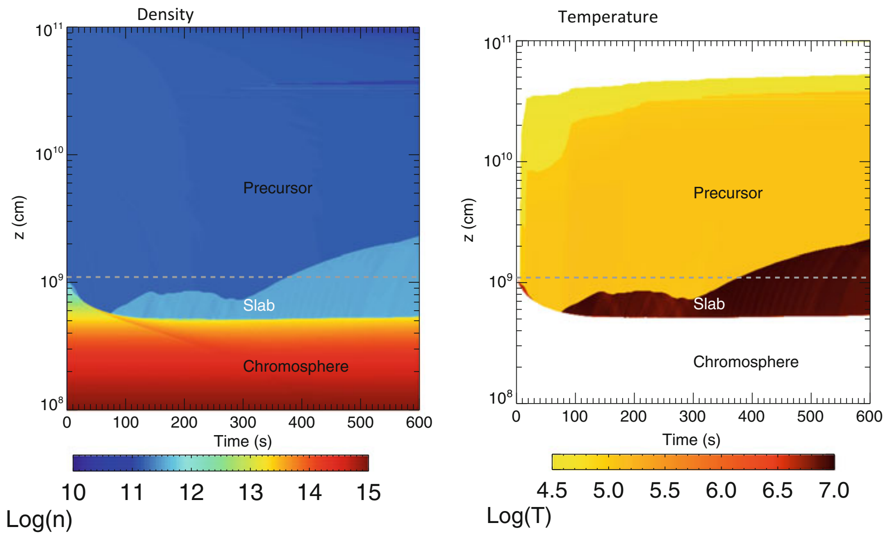

Fig. 2 Time-space plot of the density (left) and temperature (right) evolution for the simulation. The spatial extent of the shock lies in the vertical direction. The horizontal direction indicates the time. The dashed grey line indicates the initial position of the chromosphere

Moreover, the temperature map shows that the shock heats up the plasma, forming a post-shock region at 10^6 K. This region strongly radiates in UV and X-ray bands. At these wavelengths the unshocked material above is optically thick and absorbs part of the radiation. As a result, a precursor region develops. The precursor is composed of two different regions, the first one with an extension of $\approx 2 \times 10^{10}$ cm and a temperature of $\approx 5 \times 10^5$ K, the latter with a maximum extension of $\approx 4 \times 10^{10}$ cm and a temperature of $\approx 5 \times 10^4$ K. It is important to stress that, in this simulation, we assume a plane parallel geometry, which means that we consider an accretion stream with an infinite horizontal extension.

We can conclude that, RHD simulations that include, for the first time, the radiation effects in NLTE regime, suggest that:

1. Part of the UV and X-ray radiation produced by the accretion shock in CTTSs is absorbed by the upstream part of the accretion column
2. The effect of the absorption is to heat up the plasma at temperature of 10^5 K, forming a precursor region that has to be considered as a new source of UV emission in the framework of accretion phenomena

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