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RADIATIVE HYDRODYNAMIC MODELS OF ACCRETION STREAMS IN CLASSICAL T TAURI STARS

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Abstract. Classical T Tauri Stars (CTTSs) are young stars accreting mass from their circumstellar disk. According to the largely accepted magnetospheric accretion scenario, the disk extends up to the truncation radius. In this region, the magnetic field is strong enough to disrupt the inner part of the disk and to channel the material towards the star, thereby forming accretion columns. The material falls onto the star at free fall velocity and hits the stellar surface; this produces shocks that heat the plasma up to a few million degrees.

In the last twenty years, the X-ray and UV observations of these systems have raised several questions. In particular, the value predicted by theoretical models is systematically above the observed X-ray luminosity, and, also, the UV lines arising from these regions show complex profiles, which cannot be easily interpreted with current accretion models based only on magnetohydrodynamical effects. To tackle these problems, we modelled the structure and the dynamics of the plasma in the impact region, using radiation hydrodynamics simulations that include, for the first time, the effects of radiative transport in the Non Local Thermodynamic Equilibrium (non-LTE) regime.

We found that the radiation arising from the shocked plasma is partially absorbed by the unshocked accretion column. This might explain the excess of X-ray flux predicted by MHD models in which only radiative losses are considered. Moreover, due to the absorption of radiation, the pre-shock down-falling accreted material is gradually heated up to a few 10^5 K due to irradiation of X-rays arising from the shocked plasma at the impact region. We discuss the implication of this pre-shock heating for the UV and X-ray emission arising from the impact region.

Keywords: Radiation, X-Ray, UV, Radiation hydrodynamics, Accretion, Classical T Tauri Stars

1 Introduction

According to the largely accepted magnetospheric accretion scenario (Koenigl 1991), CTTSs are young stars surrounded by a disk. The disk extends internally until the, so called, truncation radius, where the magnetic field is strong enough to dominate the plasma dynamics. In this region the plasma is funneled by the magnetic field to form accretion columns that fall onto 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 temperatures within $10^5 - 10^6$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 millions degrees, producing X-ray emission (Kastner et al. 2002; Argiroffi et al. 2007).

In the last 10 years, several models, both hydrodynamic (HD) and magnetohydrodynamic (MHD), supported the explanation of the soft X-ray excess in CTTSs in terms of accretion shocks. 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 (Koldoba et al. 2008; Sacco et al. 2008). Sacco et al. (2008) proposed a 1D HD model of a continuous accretion flow impacting onto the chromosphere of a CTTS, thus assuming the ratio between the thermal pressure and the magnetic pressure to be much smaller than 1 ($\beta \ll 1$). This model reproduces the

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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 (Orlando et al. 2010, 2013; Matsakos et al. 2013), exploring those cases where the $\beta \ll 1$ approximation cannot be applied and, therefore, the 1D approximation cannot be used. These models underline the role of the magnetic field in the dynamical evolution of the post-shock region.

All the previous models do not take into account the effects of radiative gains by the matter, but only the radiative losses from optically thin plasma. The only published work where the radiation effects are considered is by Costa et al. (2017). This model is the first attempt to include the full radiative transfer (RT) effects in the framework of accretion impacts. Costa et al. (2017) 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 previously 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. Starting from these results in this work, we propose the first simulation including the radiation effects, in non-LTE regime, fully coupled with the HD equations.

2 The Model

The model describes an accretion column with uniform density of 10^{11}cm^{-3} impacting onto the surface of a CTTS. The accretion column is assumed to fall along z-axis with an impact velocity of 500 km/s, and an initial temperature of 2×10^4K. Our simulation uses the 3D radiation MHD version of PLUTO code (see below) and, for the sake of simplicity, we mimic a plane parallel structure, with the aim of following the evolution of the internal region of the accretion column. Initially, the accretion column, which is unshocked, is placed just above an idealized chromosphere, which is assumed to be at uniform temperature at 10^4K, and in radiative equilibrium for the whole simulation. Fig. 1 shows the initial conditions.

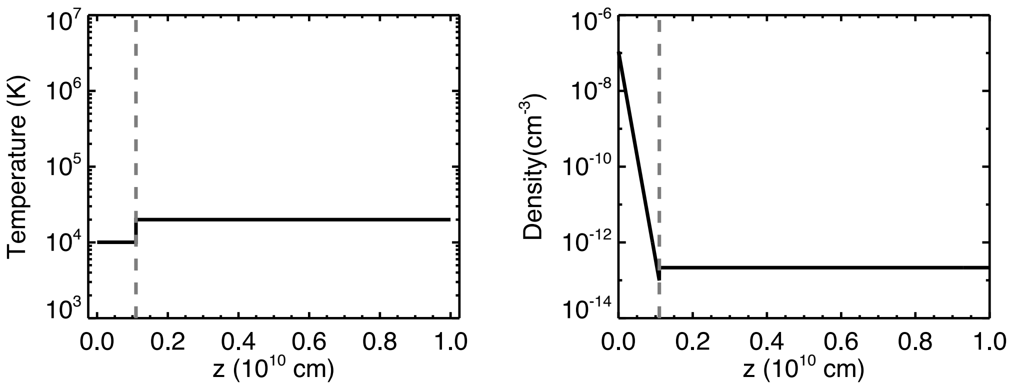

Fig. 1. Initial conditions of the simulation. Temperature (**left**) and density (**right**) profiles along z-axis. The dotted lines indicate the initial position of the chromosphere.

The model solves the equations of conservation of mass, momentum, total plasma energy (ϵ), and the comoving-frame radiation energy (E). We take into account the gravity from the central star, the thermal conduction, and the radiative heating and losses. The set of equations solved, under the flux-limited approximation, is:

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{u}) = 0 \tag{2.1}$$

$$\frac{\partial \rho \vec{u}}{\partial t} + \vec{\nabla} \cdot (\rho \vec{u} \times \vec{u}) + \vec{\nabla} p = \rho \vec{g} + \frac{\rho k_R}{c} \vec{F} \tag{2.2}$$

$$\frac{\partial \epsilon}{\partial t} + \vec{\nabla} \cdot [(\epsilon + p)\vec{u}] = \rho \vec{u} \cdot \vec{g} + \vec{\nabla} \cdot \vec{F_c} - L + k_P \rho c E \tag{2.3}$$

$$\frac{\partial E}{\partial t} + \vec{\nabla} \cdot \vec{F} = L - k_P \rho c E \tag{2.4}$$

$$p = \rho \frac{k_B T}{\mu m_H} \qquad\qquad \vec{F} = -\lambda \frac{c}{k_R \rho} \vec{\nabla} E \tag{2.5}$$

where ρ is the density, $\vec{u}$ the velocity, p the gas pressure, $\vec{g}$ the gravity, $\vec{F_c}$ the thermal conduction, c the speed of light, k_R the Rosseland mean opacity, $\vec{F}$ the comoving-frame radiation flux, k_P the Planck mean opacity, and λ the flux limiter. The equations are solved in a 3D Cartesian coordinates system (x,y,z). The total radiative properties are calculated in the non-LTE regime (Rodríguez et al. 2018)

The calculation was performed using PLUTO v4.0 (Mignone et al. 2007), a modular, Godunov-type code for astrophysical plasmas. PLUTO was coupled with a RT module, which was originally restrained to the LTE regime (Kolb et al. 2013), and which we have upgraded in order to take into account the non-LTE 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 a work in progress, so the results shown here are preliminary. The evolution of the system is shown in Fig. 2:

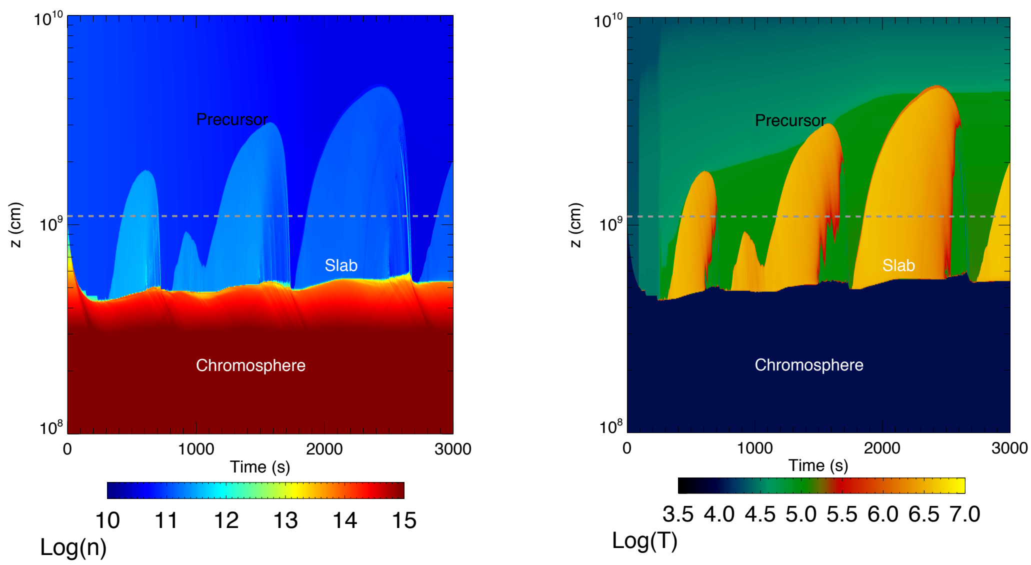

Fig. 2. Time-space maps of the density (**left**) and temperature (**right**) of the simulation. The spatial extent of the shock is along z-axis. The x-axis indicates the time. The dashed grey lines indicate the initial position of the chromosphere.

Fig. 2 shows that, initially, the accretion column is located just above the chromosphere. The accretion column sinks into the chromosphere and it stops when the chromospheric thermal pressure is equal to the ram-pressure of the accretion column. After the impact, a shock propagates through the accretion column heating up the plasma and producing a post-shock region (light blue in Fig 2 left and yellow in Fig 2 right) that extends up to $\approx 2 \times 10^9$cm, and with a temperature of 10^6K. During the expansion of the slab, the radiative losses at the base of the column increase up to a critical value, which trigger thermal instabilities that cause the collapse of the post-shock region. After the collapse, the slab forms again until it collapses again under the action of radiative losses.

The hot post-shock region strongly radiates in UV and X-ray bands. At these wavelengths, the unshocked material above absorbs part of the radiation. As a result, a precursor region develops (green region in Fig. 2 right). The precursor is composed of two different zones, a hotter one, with a temperature of $\approx 5 \times 10^5$K, and a cooler one with a temperature of $\approx 10^{4.5}$K.

It is important to stress that, in this simulation, we mimic, with our 3D code, a plane parallel geometry, which means that we consider an accretion stream with an infinite horizontal extension. This may have some implications on the quantitative description of the precursor region (in particular its extension). In any case, the aim of this work is to prove the existence of such a hot precursor region. For a more quantitative study full 2D MHD simulations are required.

In conclusion, our RHD simulations, which include, for the first time, the radiation effects in non-LTE regime, suggest that:

- Part of the UV and X-ray radiation produced by the accretion shock in CTTS is absorbed by the upstream part of the accretion column.
- The effect of the absorption is to heat up the plasma at temperature of 10^5K, 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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