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3D Gray Radiative Properties of a Radiation Hydrodynamic Model of a YSO Accretion Shock

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Abstract. We present preliminary results of radiative properties of a 1D gray radiation hydrodynamic (RHD) model of an accretion shock on a young stellar object (YSO). This model takes into account the transition between the collisional equilibrium regime (local thermodynamic equilibrium, LTE), and the coronal equilibrium regime. Based on the 1D planar structure, we built a 3D cylindrical one. Most notably, the post-shock region obtained in our case is far less extended (by a factor of 10 000) than the typical one obtained with models that assume gray optically thin radiative losses. Moreover, we find that the column is optically thin in its longitudinal dimension, and in the transverse dimension, except over an extremely narrow region ($\lesssim$ 700 m). Consequently, still under the gray assumption, the photons emitted by the hot slab can propagate through the column and escape freely in all directions, including towards the chromosphere. The radiation flux has therefore components that are perpendicular to the accretion column, which demonstrates that a multidimensional (2D or 3D) radiative model is necessary for such a cylindrical structure. This study needs to be taken forward and expanded, by improving the radiative treatment of the RHD model, through relaxation of both the gray and the LTE approximations for the calculation of opacities, in order to clarify the structure of the post-shock region, which is a major source of emission probed by observations.

1. Introduction

It is widely agreed that accretion on stars in formation, such as classical T Tauri stars (CTTSs), occurs according to the following scenario (Camenzind 1990; Königl 1991): matter from the inner part of the surrounding disk follows protostellar magnetic field lines, and falls on the stellar surface at free-fall velocity, which forms radiative shocks. The shocked material reaches millions of Kelvin, emitting soft X-ray radiation (e.g., Argiroffi et al. 2007). Many observational spectra of young stars have been obtained over the last two decades, from X-ray to near infrared, awaiting for appropriate theoretical interpretation.

Modeling an accretion shock on a young star is a major challenge, since it requires the simultaneous consideration of hydrodynamic, magnetic, and radiative effects. A large effort has been undertaken in the last few years to simulate this structure through 1D hydrodynamic and 2D MHD simulations (Sacco et al. 2008, 2010; Koldoba et al. 2008; Orlando et al. 2010; Matsakos et al. 2013; Orlando et al. 2013). In these studies, radiation is included only through a radiative loss term in the energy equation (assuming an optically thin plasma), and the radiation effect is neglected in the momentum equation. Proper treatment of radiative transfer may however play a critical role in the determination of the structure and dynamics of an accretion shock as explained below.

2. A Monodimensional Radiation Hydrodynamic Model

The influence of radiative transfer on the evolution of an accreting column was, for the first time, studied by Chièze et al. (2012) and de Sá et al. (2014). They use the 1D RHD code ASTROLABE, developed by one of the co-authors of this paper, J.-P. C. (Lesaffre et al. 2004). ASTROLABE considers plasmas composed of H, H^+, He, He^+, He^{2+}, M and M^+, where M represents a "catch-all metal" which completes, with the free electrons, the composition. The code is fully implicit, and of Adaptive-Lagrangian-Eulerian type: the spatial grid has a fixed number of points, which are free to move in order to increase the resolution in regions with large gradients. The coupling between radiative transfer and hydrodynamics is achieved through a two-moment model (the first two moments of the radiative transfer equation, RTE, are solved) that introduces the radiation energy and momentum densities, as well as the Planck and Rosseland mean opacities. The closure relation is provided by the M1 model (Levermore 1996; Dubroca & Feugeas 1999). For now, gray quantities are considered. The radiative energy source term for the gas is calculated by considering the collisional equilibrium regime (LTE) in optically thick regions and the coronal equilibrium regime in optically thin regions. The transition between both regimes is made through a parameter ζ defined such as (1-ζ) represents the escape probability of a photon, as described in de Sá et al. (2014).

An accretion shock structure has been modeled with ASTROLABE (see also §3.2 of de Sá et al. 2014). The accreting flow impinges on the stellar surface with the following upstream conditions: velocity of 400 km s^{-1}, temperature of 3000 K, density of 10^{-13}g cm^{-3}. The simulated post-shock region, or hot slab, is extremely narrow (~2 or 3 km). It is important to note the large discrepancy between the size obtained with this RHD model and the one obtained with models that assume optically thin cooling (2-3 $\times 10^4$ km). The very small size obtained with the above model is due to a particularly high cooling, which results from the chosen set of high Planck opacities used in the collisional equilibrium (LTE) regime, in comparison with the optically thin

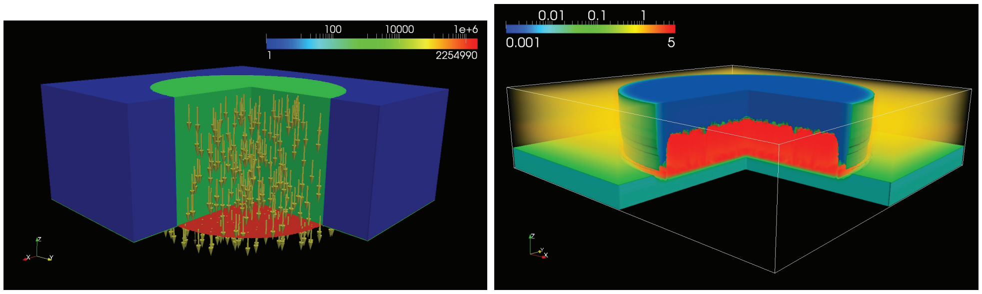

Figure 1. Snapshots (temperature T) of two accretion column models. Left: RHD (ASTROLABE 1D, T in K). The cylinder is 16×10^9 cm in diameter and 10×10^9 cm high. A transparent medium (1K, blue) is added around the column. The pre-shock region is at 3000K (green). The post-shock plasma is extremely thin ($\sim 3\times10^5$ cm), at $\sim 10^6$ K (red "pancake"). The unperturbed chromosphere is at $\sim$ 6000 K. Right: MHD (PLUTO 2D, T in MK). The corona is at $\sim$ 0.9 MK (yellow), the unperturbed chromosphere at $\sim 10^4$ K (light blue), the pre-shock region at $\sim$ 2500 K (dark blue), and the post-shock plasma at ~5 MK (red) with a thickness of $\sim 3\times10^9$ cm.

cooling case. The 2-3 $\times10^4$ km size has been obtained with a 1D model (cf. §1 of de Sá et al. 2014), as well as with a 2D MHD model provided by S. Orlando with the PLUTO code (Mignone et al. 2007, 2012): see Orlando et al. (2013) and Ibgui et al. (2014). These two models are very close, since the MHD simulation assumes that the plasma has a $\beta \ll 1$, where β = gas pressure / magnetic pressure: the plasma moves and transports energy along magnetic field lines exclusively; the 2D MHD model is, therefore, equivalent to a 1D model (Orlando et al. 2013). Figure 1 displays the two structures: the 1D RHD on the left, the 2D MHD with optically thin cooling on the right. Note that 3D structures were derived from the 1D simulation as well as from the 2D one, in order to study their radiative properties (see section 3 below and Ibgui et al. 2014).

3. Three-dimensional Gray Radiative Properties of the Accretion Column

As described above, the RHD models approximate the radiative transfer treatment by using a moment formulation. We present here our results of radiative properties of the accretion column, deduced from the resolution of the gray RTE, using the IRIS code (Ibgui et al. 2013). Such an approach provides the distribution of the specific intensity throughout the structure, from which the radiation flux distribution is inferred. Based on the 1D RHD model calculated with ASTROLABE, we built a cylindrical column of 16×10^9 cm in disc diameter (see Fig. 1 and the sketch in Fig. 2). Such a value comes from the observational result that accretion spots are characterized by filling factors of a few percents of the stellar surface (e.g., Donati et al. 2008). To fill the computational domain, we added a transparent medium around the column and above the chromosphere, so that it does not contribute to the radiation of the structure column (temperature and densities made artificially low: 1 K, and 10^{-30} g cm^{-3}).

The direction that is parallel to the accretion flow is referred to as z-direction (see Fig. 2). We first determine the transverse optical depth $\tau(D,z)$ of the column, defined throughout the diameter D of the disc, as a function of z position above the photosphere. We plot the transmission, $t(D,z) = \exp(-\tau(D,z))$, versus z, between the base of the

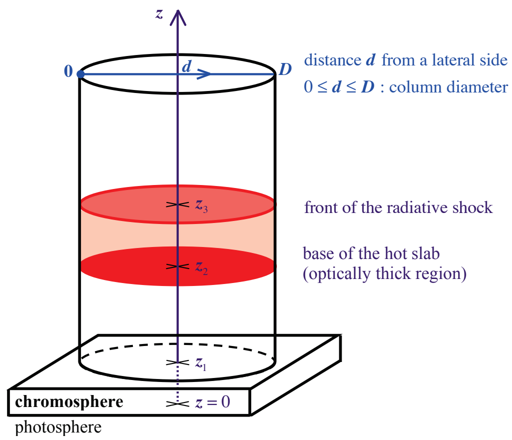

Figure 2. Sketch of the cylindrical accretion column built from the RHD 1D ASTROLABE model (drawing is not to scale). The z-axis refers to the direction along the accretion flow, and points outward from the photosphere, where z is the position above the photosphere. The transverse optical depth, $\tau(d, z)$, is defined in a plane z=constant, along the diameter, as a function of the distance d from a lateral side. D is the diameter of the column.

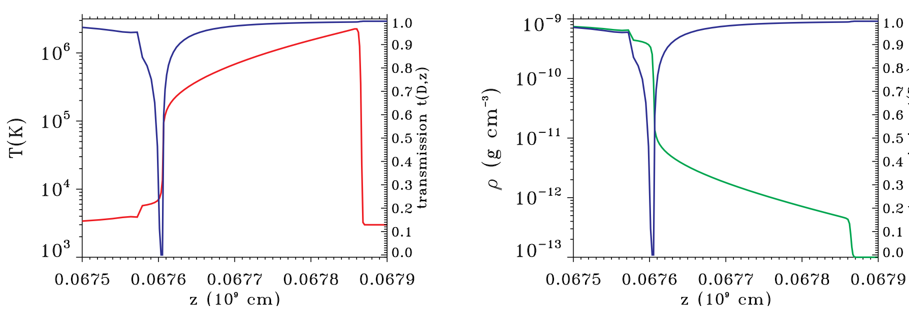

Figure 3. Temperature T(K) (red, left) and density ρ(g cm^{-3}) (green, right) of the 1D RHD structure, versus the distance z (10^9 cm) from the photosphere. The blue curve represents, in both panels, the transverse transmission of the column throughout the diameter D of the disc, $t(D, z) = \exp(-\tau(D, z))$, versus z. The limit between the chromosphere and the accreting column is at $z_1 = 0.0675 \times 10^9$ cm.

accretion column ($z_1 \approx 0.0675 \times 10^9$ cm) and the front of the radiative shock ($z_3 \approx 0.0679 \times 10^9$ cm), along with the temperature profile (red curve, Fig. 3, left), the density profile (green curve, Fig. 3, right), the Rosseland opacity, and the ζ parameter (orange curve and dashed black curve, Fig. 4, left). We see that the cross section of the accretion column is optically thin everywhere, except in an extremely narrow region ($\lesssim 700$ m) located at the base of the hot slab ($z_2 \approx 0.0676 \times 10^9$ cm), where the transmission and, therefore, the escape probability (1-ζ) approach zero, in which case the ASTROLABE radiative model falls under the collisional equilibrium (LTE) regime. The right panel of Fig. 4 depicts the transmission, $t(d, z_2)$ (blue), and the optical depth $\tau(d, z_2)$ (magenta) at position z_2, versus the distance d from a lateral side of the accreting column (cf. Fig. 2). It shows that the cross section at z_2 gradually tends toward an optically thick

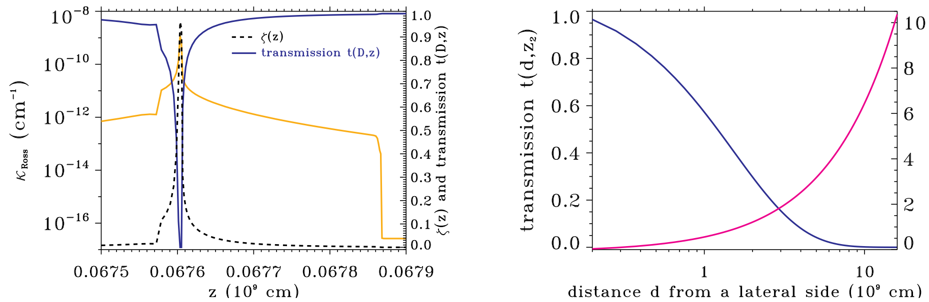

Figure 4. Left: Rosseland opacity (cm^{-1}) (orange), ζ (dashed black, 1-ζ: photon escape probability), and transverse transmission of the column throughout the diameter of the disc $t(D, z)$,versus z. Right: transverse transmission, $t(d, z_2)$, (blue) and optical depth, $\tau(d, z_2)$, (magenta) versus the distance d (10^9 cm) from a lateral side of the column, at the base of the hot slab ($z = z_2 \approx 0.0676 \times 10^9$ cm). Distance d ranges from 0 to $D = 16 \times 10^9$ cm, the diameter of the accretion column.

medium, which allows many photons to escape from the lateral sides. Note, however, that photons that are generated in the center of the column (where $d = 8.0 \times 10^9$ cm) are unlikely to escape from the lateral sides since the lateral transmission in the center is 5.0×10^{-3}. It is easy to verify that this corresponds to a photon mean free path of 1.5×10^9 cm. Importantly, the accretion column is optically thin along z-direction direction: the transmission is close to 1 from the top of the column down to the photosphere.

We finally show the distribution of the radiation flux within the structure: its magnitude (Figure 5, left), and the vector field (Figure 5, right). These pictures show evidence of flux at the side walls ($F_x = F_y \sim 2 \times 10^{13}$ erg s^{-1} cm^{-2}), of the same order of magnitude, or even greater than the axial flux at the top of the column $F_z \sim 1$ or 2×10^{13} erg s^{-1} cm^{-2}. This clearly demonstrates the need for a multidimensional modeling of radiative transfer. Not surprisingly, Fig. 5, right panel, shows a flux vector field that escapes from the hot slab.

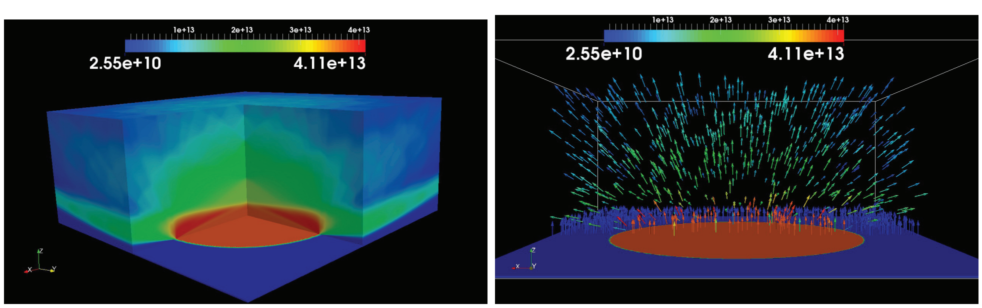

Figure 5. Distribution of the gray radiation flux magnitude (erg s^{-1} cm^{-2}) of the ASTROLABE RHD structure.

4. Conclusion and Prospects

We have presented early results of 3D gray radiative properties of a 1D gray RHD model of an accretion shock. We note the huge impact of the radiative transfer model on the size of the post-shock region, which can vary by a few orders of magnitude. In the case described here, an extremely efficient radiative cooling produced a very narrow post-shock region. A study is underway to determine the role of opacities and radiative transfer modeling on the structure of the post-shock. In the scenario presented here, we have shown that the column is optically thin, except in a very narrow region at the base of the hot slab. We have established evidence for lateral radiation flux in the post shock-region, hence the need for a multidimensional approach for the radiation modeling.

In the near future, significant progress is expected in our understanding of the dynamics and structure of accretion shocks, as we plan to relax both the gray and the LTE approximations for the calculation of opacities used in ASTROLABE. In particular, such a treatment will improve the characterization of regions in intermediate regimes, i.e., neither in optically thin nor in optically thick regimes, such as the base of the hot slab and the transition between the accretion column and the chromosphere. The latter plays a crucial role on the location of the accretion shock with respect to the photosphere, and, therefore, on the spectroscopic signature of the system.

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