HYDRODYNAMIC MODELING OF ACCRETION SHOCKS ON A STAR WITH RADIATIVE TRANSPORT AND A CHROMOSPHERIC MODEL

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Abstract. The aim of the project (ANR STARSHOCK) is to understand the dynamics and the radiative properties of accretion columns, linking the circumstellar disk to the surface photosphere of Young Stellar Objects. The hydrodynamics is computed first, using a high resolution hydrodynamic 1D ALE code (ASTROLABE) coupled to radiative transfer and line cooling, along with a model for the acoustic heating of the chromospheric plasma. Spectra are then post-processed with a 1D radiative transfer code (SYNSPEC), using DFE solver and an extended atomic database covering a wavelength range from X rays to visible.

Keywords: accretion shocks, oscillations, radiative transfer, M1 closure, cooling function, dynamical chromosphere, acoustic heating

1   Introduction

One dimensional hydrodynamic models (Koldoba et al. 2008; Sacco et al. 2008, 2010) have confirmed the radiative shock origin of the soft X-ray observations of CTTSs (Testa et al. 2004; Robrade & Schmitt 2007), showing periodic variations due to radiative instabilities. Furthermore, two dimensional MHD models (Orlando et al. 2010) have stressed the dependence of the dynamics and of the stability of accretion shocks upon the plasma parameter β. However, in these simulations, cooling of the shock heated plasma is entirely attributed to optically thin line cooling, discarding radiation transfer. This may be a crude approximation in the relatively dense part of the cooling flow, which penetrates the chromosphere. The treatment of the structure of the chromosphere itself is also simplified in these simulations, although the depth at which occurs the main accretion shock, and thus its observability, depends on the pressure profile of the chromosphere.

Our aim is to show the sensitivity of the accretion shock structure on the way the radiative transfer is treated. We report here on a first attempt to include both radiative transfer and a model of stellar chromosphere heating in hydrodynamics simulations of accretion flows on stellar surfaces.

2   Physical assumptions and model

The radiatively driven evolution of an accretion flow impacting the dynamical structure of the chromosphere of a star is modelized by solving the 1D equations of hydrodynamics coupled to radiation, encompassing the optically thick to thin plasma regimes, relevant respectively to the upper photosphere and the shocked material.

2.1   Code specificities

The 1-D ASTROLABE code is a fully implicit Adaptive Lagrangian Eulerian (ALE) code with a fixed number of mesh points, which can move independently of the fluid velocity, to adapt the resolution to the flow properties (Dorfi & Drury 1987; Lesaffre et al. 2004). The accretion column is treated with a height dependent section: it may be for instance cylindrical, conical or exponential.

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In the present application, the ionization fraction is calculated according to the Saha equation, which is here modified in order to encompass photoionization and Lyman α radiation trapping (Brown 1973; Sacco et al. 2008). The underlying assumption of instantaneous thermodynamical equilibrium, which is roughly satisfied for the chromosphere, is currently being studied. The variation of the adiabatic exponent is taken into account by including the ionization energy of atoms in the expression of the internal energy of the plasma.

Radiative transfer is described by the two time dependent equations for radiation energy (E_r) and momentum densities ($\mathcal{M}_r$), which are written in the comoving frame (Mihalas & Mihalas 1984; Lowrie et al. 2001). The necessary closure relation is obtained using the so-called $M1$ prescription, where the expression of the Eddington factor $f_{Edd} = P_r E_r$ is obtained by maximizing the entropy of the radiation field (Levermore 1996; Dubroca & Feugeas 1999). In regions where departures from thermodynamical equilibrium are weak, the terms which couple these two equations for E_r and $\vec{M}_r$ are:

$$\begin{cases} S_{E_r} & = & \kappa_P \rho c \left(aT^4 - E_r\right) \\ \vec{S}_{M_r} & = & -\kappa_R \rho \ \vec{F}_r \end{cases} \tag{2.1}$$

where we have assumed Planck and Rosseland grey opacities, κ_P and κ_R. However, in the upper, hot, low density regions, the optically thin plasma is in coronal equilibrium. This is the case in the shocked material of the accretion flow. In this case, the source term for radiative energy is $S_{E_r} = n_e n_H \Lambda(T)$, where n_e and n_H are respectively the volume densities of electrons and of hydrogen nuclei, and $\Lambda(T)$ is the plasma cooling function; in the present work we use the cooling function of Kirienko (1993). The source term of the radiation momentum vanishes: $\vec{S}_{M_r} \approx 0$.

## 2.2 A generic model for chromosphere

Models of stellar chromosphere generally provide temperature and density profiles in hydrostatic equilibrium, adjusted to fit the observed chromospheric spectrum. An ad hoc heating function (E_H, using the notation of Peres et al. 1982) may be derived as a function of the radius, in order to maintain the equilibrium of chromosphere. The energy input E_H mimics actual energy deposition by sound waves, Alfvén waves and electronic conduction, which, since the pioneering work of Biermann (1946) and Schwarzschild (1948), are thought to heat the chromospheric layers. However, this procedure cannot be unambiguously adopted to determine the depth of the stagnation point of the accretion flow in the chromosphere, which depends crucially on the structure of the (unsteady) pressure profile of the upper stellar atmosphere. Our first approach has been to include the acoustic, dynamical, heating of the chromosphere in the global accretion model, leaving to further 3D calculations chromospheric heating by hydromagnetic waves. The aim here is to get a self-consistent, fully hydro-radiative description of the chromospheric structure, impacted by the accretion flow.

Thus, we have investigated the behavior of acoustic waves on the structure of the outer layers of a star (we choose the Sun for comparisons with theoretical models and observations, (see e.g. Rammacher & Ulmschneider 1992; Kalkofen 2007). Mechanical energy is supplied at the base of the simulation domain (at $\tau \geq 1$), in the form of a monochromatic sinusoidal motion of the first (Lagrangian) interface. Heating of the corona is not taken into account, since the later is readily crushed by the accretion flow. Figure 1 shows the formation of travelling shocks, induced by acoustic waves. Heating of the chromosphere is the result of the time-averaged temperature structure above the photosphere.

3   First results

The main features of accretion flows, especially their periodic behavior, are conserved when they interact with a dynamic chromosphere modelized as described previously. This is illustrated by Figure 2 (left), which presents a complete cycle, with the formation of the reverse shock, followed by the cooling of the shocked material which induces the formation of a second shock in the upper chromosphere, the crushing of the whole structure on the chromosphere, and again the renewal of a reverse shock. The oscillation period is about 300 s. However, the structure of the flow at the base of the accretion column is significantly modified both by radiative transfer and by the dynamics of the chromosphere. It turns out that a crucial issue is the treatment of the transition between the collision dominated plasma (inner regions) and the non equilibrium external regions, where coronal equilibrium prevails.

The effect of radiative transfer on the global structure of the accretion shock has been explored by varying the photon absorption probability in the column, from zero (optically thin line cooling (Sacco et al. 2008)) to a finite
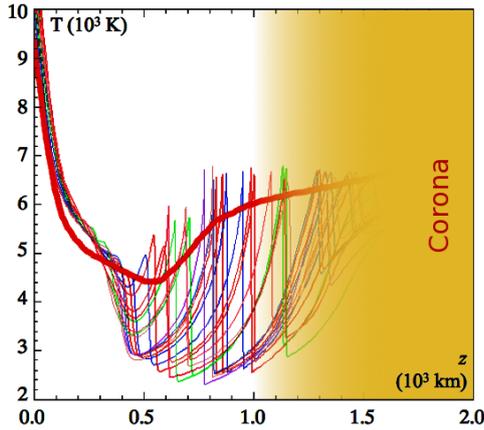
Fig. 1. Formation and propagation of shock waves induced by sound waves with initial energy flux (at $z = 0$ km) of 10^8 $erg.cm^{-2}.s^{-1}$ and a period of 60 s. The thin lines are successive snapshots of the temperature structure of the chromosphere and the thick line represents the mean temperature of the solar chromosphere (Th. Lanz, private communication). Above 500 km, acoustic waves degenerate into shocks, which strength is governed by the balance between steepening in the pressure gradient and dissipation.

value, depending on the opacity and the transverse size of the column. For example, with opacities obtained from the OP and Semenov libraries, and a column cross section of 1000 km, the accretion shock, contrary to the optically thin case, is now stationary and deeply buried in the stellar chromosphere (Figure 2, right). In view of the dramatic effects of radiation transfer, new extensive Planck and Rosseland opacity tables are currently established in the framework of an upgrade of the spectral synthesis code Synspec (Hubeny & Lanz 2011), to be used with a multigroup extension of the M1 method.
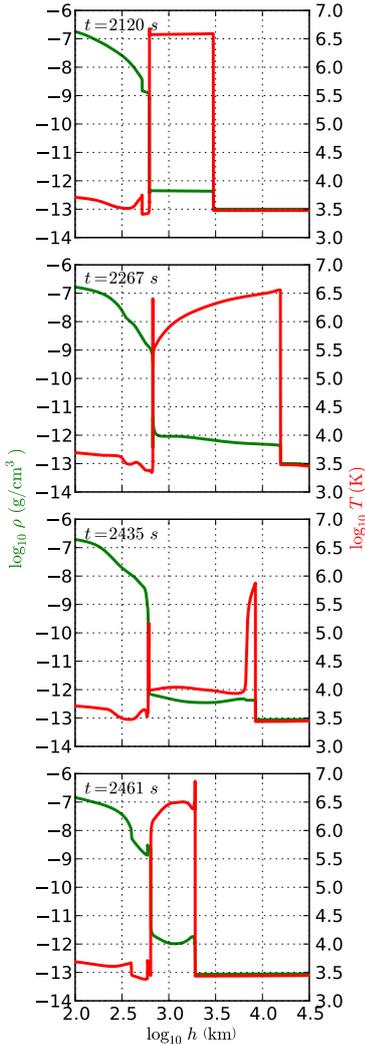
Fig. 2. Shock cycle showing snapshots of the density ρ (green line) and temperature T (red line). The gas is infalling from the right to the left on a dynamically heated chromosphere (cf. Figure 1).

Left: The accreted gas is cooled using optically thin line cooling. From top to bottom: a reverse shock forms and propagates outwards; the shocked material cools down under quasi isochoric conditions: a strong inwardly directed pressure gradient forms, which launches a second shock into the chromosphere; the whole structure is finally crushed on the chromosphere, and a new reverse shock forms. The period of this cyclic evolution is about 300 s. Cycle n°20 is shown here.

Right: In this case, the energy exchange rate between matter and radiation is not restricted to strict optically thin line cooling. According to the photon escape probability, this rate is interpolated between Eq. (2.1), through Planck and Rosseland (mean) opacities, and the optically thin regime. Enabling radiative transfer dramatically increases the cooling efficiency, so that the accretion shock turns to be stationary, apart from a periodic motion induced by the chromospheric heating.
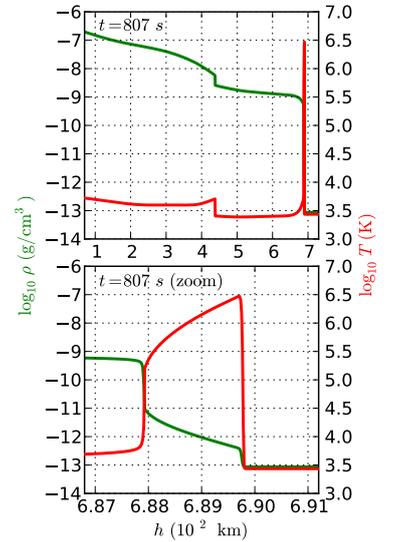
4   Conclusion

The numerical model outlined in this paper includes for the first time the treatment of the radiative transfer in the flow and a self-consistent model of the stellar chromosphere, in order to precisely characterize the thermodynamical and radiative properties of the densest part of accretion column, which is the strongest XUV emitter. In a next step, a grid of models will be calculated in order to post-process the detailed spectra emerging from these structures.

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