

MAGNETOHYDRODYNAMIC MODELING OF THE ACCRETION SHOCKS IN CLASSICAL T TAURI STARS: THE ROLE OF LOCAL ABSORPTION IN THE X-RAY EMISSION

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Received 2014 September 15; accepted 2014 October 6; published 2014 October 28

ABSTRACT

We investigate the properties of X-ray emission from accretion shocks in classical T Tauri stars (CTTSs), generated where the infalling material impacts the stellar surface. Both observations and models of the accretion process reveal several aspects that are still unclear: the observed X-ray luminosity in accretion shocks is below the predicted value, and the density versus temperature structure of the shocked plasma, with increasing densities at higher temperature, deduced from the observations, is at odds with that proposed in the current picture of accretion shocks. To address these open issues, we investigate whether a correct treatment of the local absorption by the surrounding medium is crucial to explain the observations. To this end, we describe the impact of an accretion stream on a CTTS by considering a magnetohydrodynamic model. From the model results, we synthesize the X-ray emission from the accretion shock by producing maps and spectra. We perform density and temperature diagnostics on the synthetic spectra, and we directly compare the results with observations. Our model shows that the X-ray fluxes inferred from the emerging spectra are lower than expected because of the complex local absorption by the optically thick material of the chromosphere and of the unperturbed stream. Moreover, our model, including the effects of local absorption, explains in a natural way the apparently puzzling pattern of density versus temperature observed in the X-ray emission from accretion shocks.

Key words: accretion, accretion disks – magnetohydrodynamics (MHD) – shock waves – stars: pre-main sequence – X-rays: stars

Online-only material: color figures, animation

1. INTRODUCTION

Mass accretion processes onto classical T Tauri stars (CTTSs) generate shocks at the stellar surface as the accreting material impacts at supersonic infall velocities (typical values: 200–500 km s^{−1}). The impacts generate slabs of post-shock plasma with temperature of a few millions of degrees and high density ($n > 10^{11}$ cm^{−3}), emitting soft X-rays (Calvet & Gullbring 1998; Kastner et al. 2002; Schmitt et al. 2005; Günther et al. 2006). Hydrodynamic and magnetohydrodynamic (MHD) models of radiative accretion shocks support this scenario (e.g., Koldoba et al. 2008; Sacco et al. 2008; Orlando et al. 2010, 2013; Matsakos et al. 2013). Recently, further support has been noted from spatially resolved observations of impacts by dense fragments falling back in the Sun that show many analogies with accretion stream impacts (Reale et al. 2013).

The possibility of studying the X-ray emission from accretion impacts in CTTSs is a fundamental tool to check the physical conditions of the material accreting from the disk onto the star. In fact, X-ray spectra of CTTSs, due to the density diagnostics offered by the He-like triplets, provide us with detailed information on the density and temperature structures of the hot post-shock region.

However, several aspects related to the X-ray emission from accretion shocks are still unclear and are under debate in the literature. In particular, the spectral analysis of the soft X-ray emission, believed to originate from the impact region, shows that in all the cases for which high-resolution spectra are available, the density derived from the O VII forbidden-to-

intercombination (f/i) line ratio is always lower than that derived from the Ne IX f/i ratio (Günther et al. 2006; Brickhouse et al. 2010). Considering that Ne IX originates from plasma hotter than that producing the O VII (4 MK versus 2 MK, respectively), this result has been considered at first glance in contrast with one-dimensional (1D) stationary models (Günther et al. 2007) of post-shock region that indicate an increasing density and a decreasing temperature moving down in the post-shock region. Other scenarios have been proposed to interpret the observations, invoking the interaction between the accretion stream and the surrounding stellar corona (Brickhouse et al. 2010).

Another debated issue is the evidence that the mass accretion rates derived from X-rays are significantly lower than the mass accretion rates derived from other spectral bands (UV/optical/NIR observations; Curran et al. 2011), and that the observed X-ray luminosity in accretion shocks is, in general, well below the predicted value (Argiroffi et al. 2009).

The local absorption, due to pre-shock material and surrounding chromosphere, is expected to play a fundamental role and could reconcile the above open issues. A first attempt to investigate the theoretical observability of shock-heated accreting material in the X-ray band has been done by Sacco et al. (2010) through 1D hydrodynamic modeling. These authors have pointed out the importance of the absorption from the optically thick material of the chromosphere in the post-shock plasma components that produce observable emission in the X-ray band. However, their analysis was based on 1D models and on a simple description of the absorption effect, preventing a detailed study of the observability of the X-ray emission from the impact region.

In this Letter, we investigate the accretion shock properties in the X-ray band, properly taking into account geometry and absorption, with the aim of addressing the above open issues of the accretion theory. To this end, we consider a two-dimensional (2D) MHD numerical model describing the impact of an accretion stream onto the surface of a CTTS. From the model results, we synthesize the X-ray emission and explore the observability of the post-shock plasma. The X-ray emission is synthesized by considering the local absorption by optically thick plasma for different viewing angles of the impact region and for different wavelengths. We focus on the emission line fluxes, which are traditionally used for the density diagnostic in the observed spectra, namely, the triplets of the He-like O VII (21.60, 21.80, 22.10 Å), Ne IX (13.45, 13.55, 13.70 Å), and Mg XI (9.17, 9.23, 9.31 Å) lines with the aim of providing useful diagnostics for a detailed and accurate interpretation of the observations.

2. MHD MODELING AND SYNTHESIS OF X-RAY EMISSION

For our purposes, we performed 2D MHD simulations describing the impact of an accretion stream onto the chromosphere of a CTTS. We adopted the model described in Orlando et al. (2010). The stream impact is modeled by numerically solving the time-dependent MHD equations of mass, momentum, and energy conservation in a 2D cylindrical coordinate system (r, z), assuming axisymmetry. The MHD model includes the gravity, the radiative cooling, and the magnetic-field-oriented thermal conduction (including the effects of heat flux saturation). The model also considers a detailed description of the stellar atmosphere, from the chromosphere to the transition region, and to the corona. The MHD model is implemented using PLUTO (Mignone et al. 2007), a modular Godunov-type code for astrophysical plasmas.

The star and accretion flow parameters of the simulations have been chosen in order to describe accretion stream impacts that are able to produce detectable X-ray emission (see also Sacco et al. 2010). The set of parameters chosen describes a typical X-ray-emitting accretion stream as observed in MP Mus (Argiroffi et al. 2007) or TW Hya (Kastner et al. 2002). At odds with Orlando et al. (2010), we consider a stream characterized by a radial distribution of density (as obtained from three-dimensional (3D) MHD simulations by Romanova et al. 2004), with $n_{\text{str}} = 5 \times 10^{11} \text{ cm}^{-3}$ at the center of the stream and $n_{\text{str}} = 5 \times 10^{10} \text{ cm}^{-3}$ at the border, propagating through a uniform stellar magnetic field with strength $B = 500 \text{ G}$ oriented along the z axis. The stream is initially in pressure equilibrium with the stellar corona and has a circular cross section with a radius $r_{\text{str}} = 10^{10} \text{ cm}$. We follow the stream evolution for about 3000 s.

From the evolution of the temperature, density, and velocity of the plasma in the 2D spatial domain, we reconstruct the 3D spatial distributions by rotating the 2D slab around the symmetry z axis. From the values of emission measure (EM) and temperature in each computational cell, we synthesize the corresponding emission using the CHIANTI atomic database (Landi et al. 2012) and assuming metal abundances of 0.5 of the solar values (as deduced from X-ray observations of CTTSs; Telleschi et al. 2007). The spectral synthesis takes into account the Doppler shift of lines due to the component of plasma velocity along the line of sight (LOS). The local absorption is accounted for by computing the X-ray spectrum from each cell and by filtering it through the absorption column density along

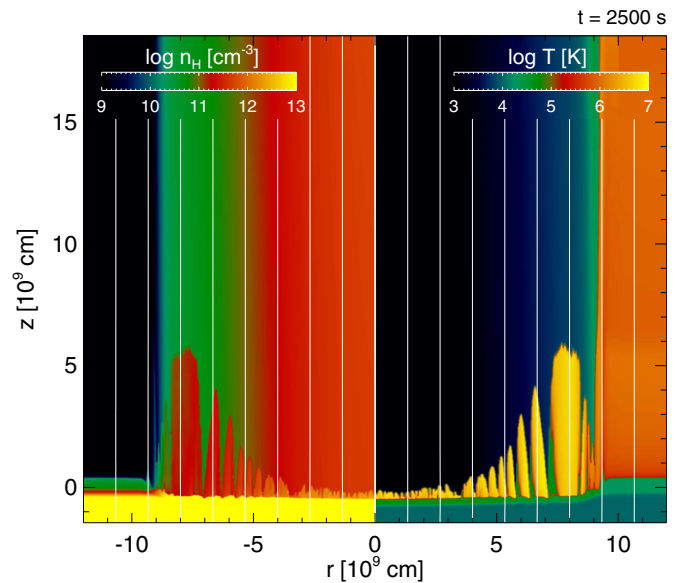


Figure 1. Density (left) and temperature (right) 2D map as derived from the model at 2500 s.

(An animation and a color version of this figure is available in the online journal.)

the LOS. The absorption is computed using the absorption cross sections as a function of wavelength from Balucinska-Church & McCammon (1992). Note that the bulk of the absorption originates within relatively cold material, given that the soft X-ray opacity drops at high temperature ($T > 10^6 \text{ K}$), as shown by Krolik & Kallman (1984). The local absorption originates from the optically thick material distributed around the post-shock region belonging to the unperturbed stream above the hot slab and to the perturbed chromosphere that may surround the slab. By integrating the absorbed X-ray spectra from the cells in the entire spatial domain, we derive X-ray images and spectra emerging from the impact region. We computed the emerging spectrum at different times in order to take into account the intrinsic variability of the post-shock region. In this context, we subtract the emission from the coronal component and do not consider the absorption due to the interstellar medium.

In the following, the synthetic maps and spectra of X-ray emission are used to explore the effects of the local absorption on the observability of the X-ray-emitting plasma and the effects of the geometry of the system by exploring different points of view at which the impact region is observed.

3. RESULTS

The evolution of the accretion impact and of the post-shock plasma are shown in the animation (see Figure 1) provided in the online journal showing the 2D spatial distributions of mass density and temperature. The simulation shows that the accreting material flows along the magnetic field lines and a hot slab is generated at the base of the accretion column. During the entire evolution, the plasma beta is < 1 in the stream, and, in particular, in the shocked slab. Thus, the magnetic field prevents mass and energy exchange across field lines and the stream is structured as a bundle of fibrils, each independent of the others. A detailed study of the physical properties of the fibrils is discussed in Matsakos et al. (2013). In each fibril, the shock position oscillates due to intense radiative cooling at the base of the slab, with alternating phases of expansion and collapse of the post-shock region. During the expansion phase, the

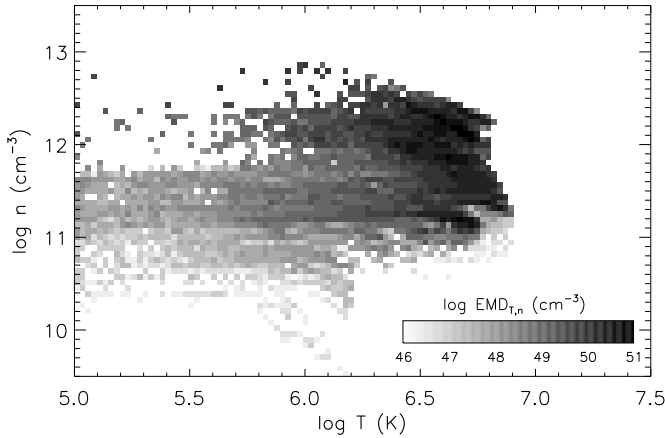


Figure 2. Emission measure distribution as a function of temperature and density derived from the model at 2500 s of evolution.

post-shock temperature is higher than during the collapse (e.g., see Figure 3 of Orlando et al. 2013). The slightly different mass density of the fibrils results in different instability periods, as also by random phases of the oscillations after few cycles.

As the stream density varies radially, the stand-off height of the hot slab⁵ is minimum (maximum) at the stream center (border). Figure 1 shows maps of density (left panel) and temperature (right panel) at the labeled time.

We derived the EM distribution as a function of temperature and density from the 2D model (Figure 2). It is evident that the simplistic scenario of a plane-parallel stratified structure fails to be valid as a complex distribution of density and temperature of

the post-shock region is found. Our detailed numerical model reveals the complexity of the shock and post-shock region.

We derived synthetic maps and spectra in the X-ray band from the model. All the fibrils contribute to the X-ray emission. The resulting spectrum integrates the contribution of the independent fibrils with different densities and temperatures that compete to the phase of oscillation. Figure 3 shows maps of X-ray emission derived from the model relative to the O VII and the Ne IX triplets emission (upper left and right panels, respectively) at an angle between the LOS and the accretion stream $\alpha = 45^\circ$ and with the effects of local absorption and Doppler shift taken into account. The synthetic maps show that the local absorption from the accretion stream heavily obscures the central (denser) part of the accretion shock in the O VII band, while in the Ne IX band, where the effects of the absorption are smaller, we can see deeper inside the accretion stream. Figure 3 (lower panels) shows the spectral region near the O VII (left panel) and Ne IX (right panel) triplets averaging over different frames (between 2000–2500 s). When the absorption is taken into account, the flux of the lines can be heavily reduced. The amount of reduction depends on the angle α and is due mainly to the dense pre-shock accretion stream. The effects of absorption appear to be dominant for $\alpha = 30^\circ$ (see Figure 3, lower panels). We investigated how accurately the unabsorbed X-ray luminosity of the accretion shock can be inferred from the emerging X-ray spectrum. To this aim we derived the absorbing column N_H by the observed ratio of the O VII resonance line at $21.60 \text{ \AA}$ to the O VII line at $18.63 \text{ \AA}$, and starting from this N_H we computed the unabsorbed flux of the O VII resonance line. We found that the unabsorbed flux was underestimated with respect to the correct value by a factor of two in the case of $\alpha = 30^\circ$ (1.8 and 1.5 for $\alpha = 45^\circ$ and 85° , respectively). Hence the *average* N_H value inferred from the emerging spectrum is underestimated, likely because the most

⁵ Which depends on the pre-shock density (Sacco et al. 2010).

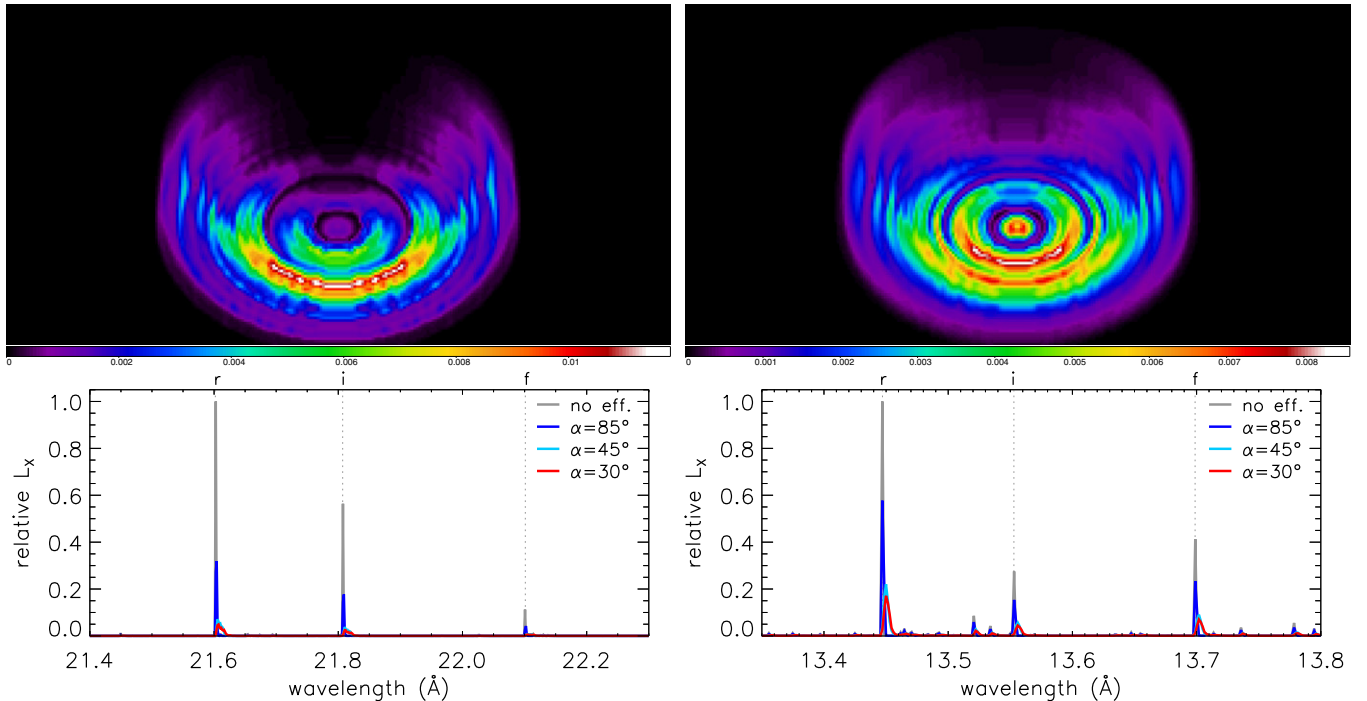


Figure 3. Upper panels: enlargement of the X-ray-emitting impact region. The emission is synthesized from the model at 2500 s for O VII (left panel) and Ne IX (right panel); the LOS of the observer forms an angle of $\alpha = 45^\circ$ with respect to the stream axis. Lower panels: spectral region near the O VII (left panel) and Ne IX (right panel) triplets derived from the model. Each spectrum (in units of ph/s/bin; blue line: $\alpha = 85^\circ$; cyan line: $\alpha = 45^\circ$; red line: $\alpha = 30^\circ$) is divided by the maximum value of the unabsorbed spectrum (gray line) in the plotted range. The effects of local absorption and Doppler shift are taken into account.

(A color version of this figure is available in the online journal.)

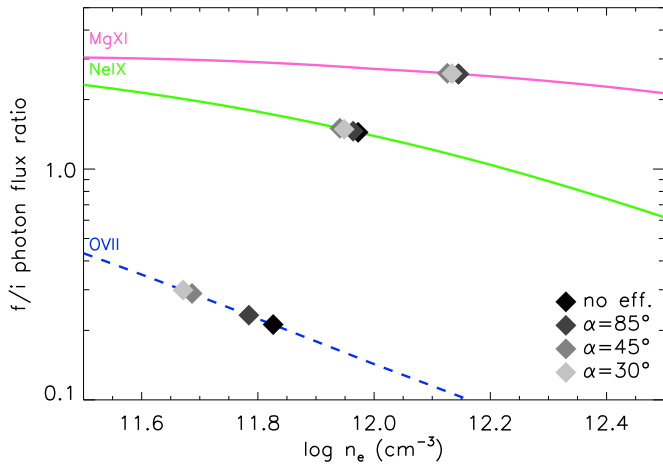


Figure 4. Ratios of forbidden-to-intercombination line fluxes as a function of density for several He-like lines (O, Ne, and Mg) with the values (diamond) derived from our analysis.

(A color version of this figure is available in the online journal.)

absorbed portions of the post-shock region do not significantly contribute to the emerging spectrum.

We used the total synthetic spectra to investigate the evidence that the shocked plasma appears denser at higher temperatures (Brickhouse et al. 2010). To this end, we apply to the spectra the same density diagnostic techniques commonly used to analyze observed spectra and based on the f/i flux ratio derived for several He-like lines (Gabriel & Jordan 1969; Porquet et al. 2001). Figure 4 shows the f/i line fluxes as a function of density for several He-like triplets (O, Ne, and Mg) synthesized from the model.

We find that plasma components of the shocked slab with higher temperatures are also characterized by higher densities, in full agreement with the observations, and in particular this trend is amplified when the local absorption effect is taken into account. In fact, when a 2D MHD model of the stream impact is applied, as the one developed by us in this case, the complexity of the emitting region is evident. In particular, the distribution of density versus temperature is far from that expected for a plane-parallel stratified structure of the post-shock region. Furthermore, the local absorption prevents us from the observation of deeper and denser regions for more absorbed emitting regions. This effect is different for the different triplets inspected. In fact, the softer part of the spectrum suffers a higher absorption: the O VII triplet, which originates at a lower temperature than the Ne IX triplet, is more absorbed, and then we cannot observe as deep in the wavelengths of the O VII triplet as we can in Ne IX energy band (compare the upper left and right panels of Figure 3). Therefore, when the absorption is taken into account, the Ne IX emitting plasma appears denser (as we can observe deeper) than the O VII emitting region (see Figure 4).

4. DISCUSSIONS AND CONCLUSIONS

The X-ray emission from accretion shocks detected in CTTs opens several issues in both observations and models. In particular, the evidence that the X-ray luminosity in accretion shocks is below the predicted value and that the density versus temperature structure of the shocked plasma is not in agreement with the simplified picture of the post-shock region urges us to

investigate whether a correct treatment of the local absorption by the surrounding medium can significantly affect the observed X-ray emission.

To address these issues, we consider a 2D MHD model describing accretion stream impacts in CTTs. We explore the effect of a density-structured stream on the emerging X-ray emission. We synthesize the X-ray emission of the post-shock plasma from the model results, including the effects of the local absorption and by taking into account that the contribution to the absorption differs for different components of the hot post-shock medium, different inclination angles, and different inspected wavelengths.

We find that the X-ray emission originating in the shocked slab can be heavily reduced due to the absorption by the optically thick material surrounding the slab. Moreover, different regions of the post-shock suffer very different extinctions, as shown in Figure 3 (upper panels), with some regions being completely obscured. As a consequence, any average extinction derived from the data, and hence the amount of emitting plasma, could be significantly underestimated.

This has a direct implication on the derivation of the mass accretion rate in the X-ray band which is expected to be largely underestimated, in agreement with observations. At the same time, the point of view from where the impact region is observed plays a crucial role because of the different distribution of the optically thick material along the LOS.

Our results demonstrate that it is necessary to adopt an appropriate description of the local absorption together with a realistic model that properly describes the accretion shock to reveal the complexity of the emitting region. We verified that the post-shock plasma presents a complex distribution of density and temperature. We also found that the observation of deeper and denser regions is hampered in the soft X-rays (e.g., at the energies of the low temperature O VII triplet) because of the local absorption, thus explaining why the cooler plasma also appears more tenuous. By directly comparing our model results with observations, we confirm that the observed evidence that components with higher temperatures are also characterized by higher densities, a trend so far not explained, can be explained in a natural way by a detailed and realistic model.

Pluto was developed at the Turin Astronomical Observatory in collaboration with the Department of General Physics of Turin University. We acknowledge the CINECA Award No. HP10BG6HA5, 2012 for the availability of high performance computing resources and support, and the computer resources, technical expertise, and assistance provided by the Red Espanola de Supercomputacion (award N. AECT-2012-2-0001). T.M., L.I., and C.S. acknowledge the support of the ANR STARSHOCK project ANR-08-BLAN-0263-07-2009/2013. T.M. was supported in part by the NASA ATP grant NNX13AH56G. L.I. and C.S. acknowledge the support of Labex Plas@par (ANR-11-IDEX-0004-02).

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