X-ray spectra of CTTS

Modelling the accretion shock

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Abstract

Classical T Tauri stars (CTTS) are young, accreting pre-main sequence objects. An accretion funnel is thought to follow dipolar magnetic field lines and to impact at high stellar latitude. A 1D non-equilibrium stationary model of the post-shock accretion zone is presented. Fitting this to grating X-ray observations of CTTS TW Hya with XMM-Newton and *Chandra*, putting special emphasis on the density and temperature sensitive He-like triplets of O VII and Ne IX, allows to accurately measure the infall velocities, which turn out to match the free-fall velocity of 525 km/s, and the infall densities. The total intensity directly translates into a mass accretion rate of about 2×10^{-10} $M_\odot \mathrm{yr}^{-1}$, less then determined in the UV oder optical range. This may possibly be due to inhomogeneities in the spot, because in X-rays we probe only the hottest part of the post-shock zone. Applying the model, the total emission can be decomposed into an accretion part, which explains the soft X-rays, and a hot corona, fitted by 2 standard APEC components. The already known metal depletion is confirmed.

The Model

The accreted material follows the field lines and impacts on the stellar surface (Shu et al. 1994). A shock develops, where the ram pressure equals the thermodynamic pressure of the surrounding stellar atmosphere (for a sketch see Fig. 1). We use a two-fluid approach with an atomic/ionic component and an electronic component.

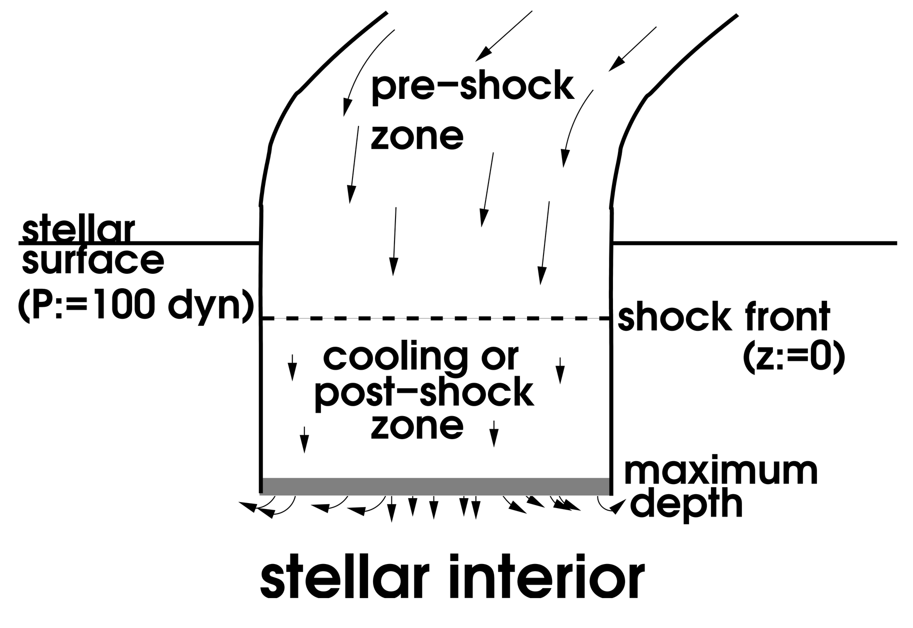

Figure 1: A sketch of the accretion shock geometry.

The shock is treated as a mathematical discontinuity, where the ion gas gets heated according to the Rankine-Hugoniot conditions. Marking the state in front of the shock front by the index 0, that behind the shock by index 1, they become

$$\rho_0 v_0 = \rho_1 v_1 \quad (1)$$
$$P_0 + \rho_0 v_0^2 = P_1 + \rho_1 v_1^2 \quad (2)$$
$$\frac{5P_0}{2\rho_0} + \frac{v_0^2}{2} = \frac{5P_1}{2\rho_1} + \frac{v_1^2}{2}, \quad (3)$$

where v denotes the bulk velocity, ρ the total mass density of the gas and P its pressure. To a first approximation the electronic component is just compressed adiabatically, because the viscosity in the electron gas is far smaller than in the ion gas, implying a rise of the temperature T according to

$$T_{e_1} = T_{e_0} \left(\frac{\rho_1}{\rho_0}\right)^{(\gamma-1)} \quad (4)$$

with $\gamma = 5/3$ denoting the adiabatic index.
In the post shock cooling zone we stepwise integrate the hydrodynamic and the ionization equations under the following assumptions:

- No heat conduction
- No viscosity
- Maxwell distribution in each component
- Stationarity of problem
- No optical depth effects
- Magnetic field $\vec{B} \| \vec{v} \Rightarrow$ The magnetic field does not influence the flow.
- Hydrodynamics and atomic physics can be treated separately during each step.

This leads to an ODE for the ion temperature T_{ion} in depth z:

$$v \frac{\mathrm{d}}{\mathrm{d}z}\left(\frac{3}{2} k T_{\mathrm{ion}}\right) + v n k T_{\mathrm{ion}} \frac{\mathrm{d}}{\mathrm{d}z}\left(\frac{1}{n}\right) = -\omega_{ei} \quad (5)$$

for the ions with number density n. ω_{ei} describes the heat flow from the ions to the colder electrons according to Coulomb interactions. We obtain a density and temperature structure (see Fig. 2) of the shock and model the resulting spectrum, especially the He-like triplets of O and Ne. We vary the infall velocity v_0, the infall density n_0 and the abundances of C, N, O, Ne, Mg, Si, S and Fe.

Results

In this section some results on the shock structure are presented, as an example a shock with the parameters $n_0 = 10^{12}$ cm^{-3}, $v_0 = 525$ km s^{-1} and chemical abundances as found in TW Hya (our fit) is used. As the shock-heated gas looses energy by radiation, it cools down and the density increases. Temperature and density profiles are shown in Fig. 2.

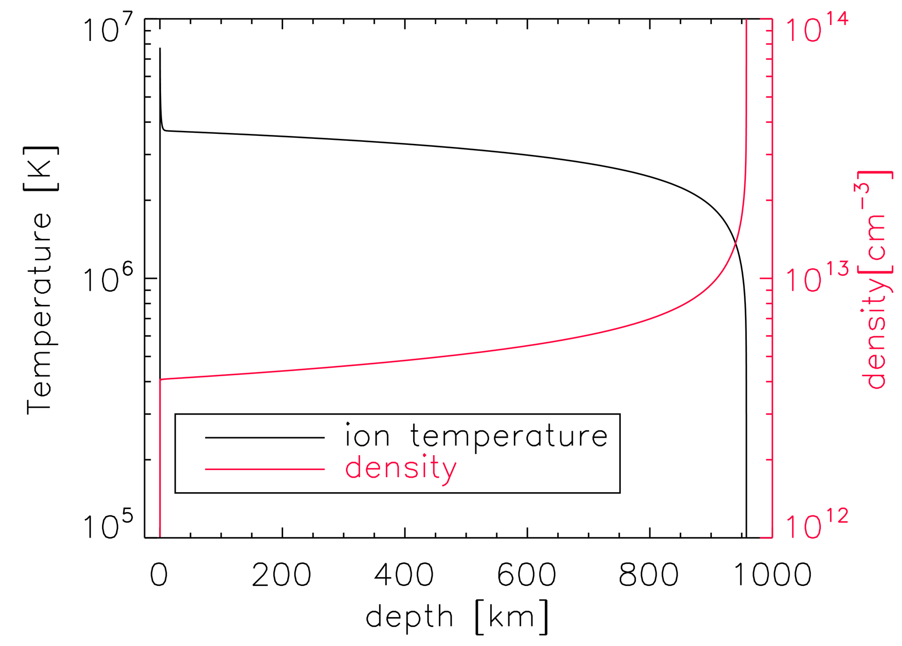

Figure 2: Temperature and density profiles

Due to decreasing temperatures with depth, different ionization stages are present at different prositions. Immediately behind the shock, the gas is in non-equilibrium, until the highest ionization stages are reached. In the following the gas slowly recombines, while the density in creases.

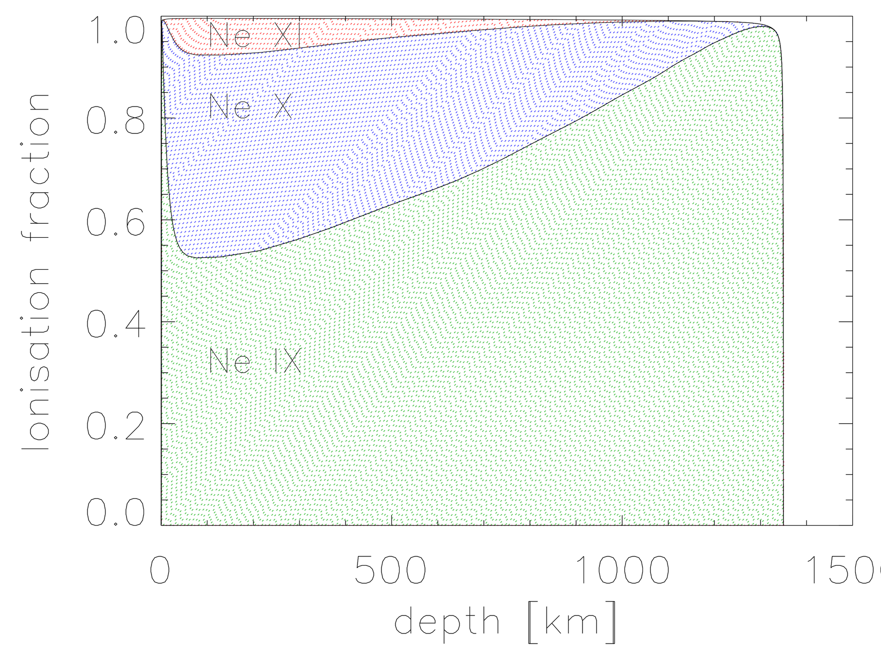

Figure 3: Ionization state of Ne in different depth

The emission observed is the sum of the radiation from all layers and represents therefore no unique set of conditions. The resulting O VII f/i ratio for different v_0, n_0 and different background radiation temperatures is shown in Fig. 4.

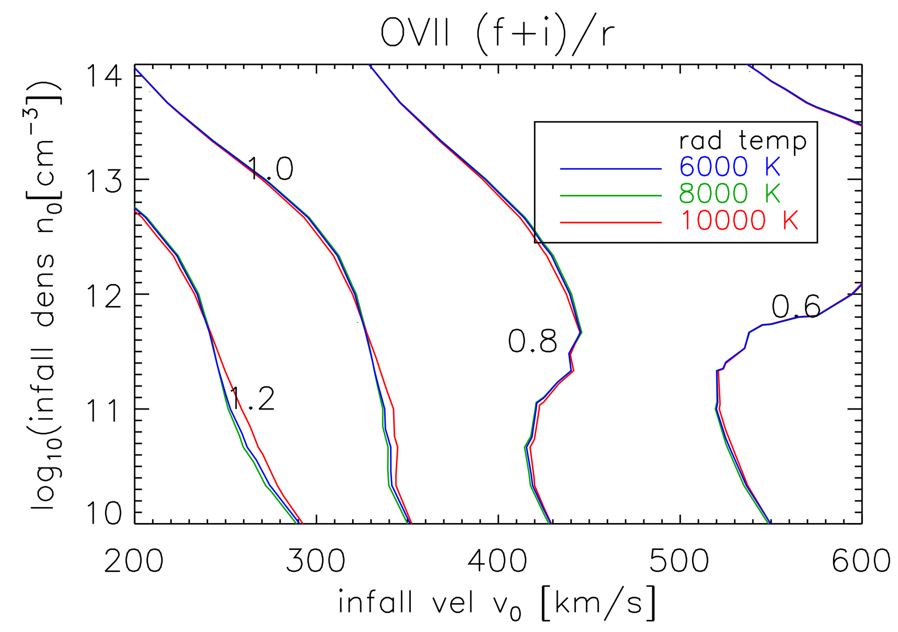

Figure 4: O VII f/i ratio for different v_0, n_0 and background radiation temperatures.

The example of TW Hya

TW Hya is the best-studied and nearest CTTS (57 pc Wichmann et al. 1998), a K7-M1 star, about 10 Myr old, $M_* \approx 0.7$ $M_\odot$(Webb et al. 1999). It was observed with *Chandra* for 48 ks (Kastner et al. 2002) and with XMM-Newton for 30 ks (Stelzer & Schmitt 2004). The model was calculated for a grid of v_0, n_0 and different abundances and red into XSPEC as a table model. It was fitted simultaneously with low-density APEC models, which represent a corona. The best fit model has the parameters given in table 1, the abundances are relative to Grevesse & Sauval (1998).

v_0	525 km/s
n_0	10^{12} cm^{-3}
filing factor	0.2%
$\dot{M}$	2×10^{-10} $M_\odot$/yr
χ^2 (dof)	1.57(577)
abundances	
O	0.25 ± 0.04 (stat. error)
Ne	2.46 ± 0.06 (stat. error)
Fe	0.19 ± 0.01 (stat. error)
flux (energy band 0.3-2.5 keV)	
shock	3.7×10^{12} erg/cm^2/s
corona	2.0×10^{12} erg/cm^2/s

Table 1: best fit for TW Hya

In Fig. 5 we show the observed EPIC spectrum of TW Hya together with our best fit model; the soft component turns out to be dominated by accretion but the hard X-rays cannot be produced in an accretion shock, but originate in a corona.

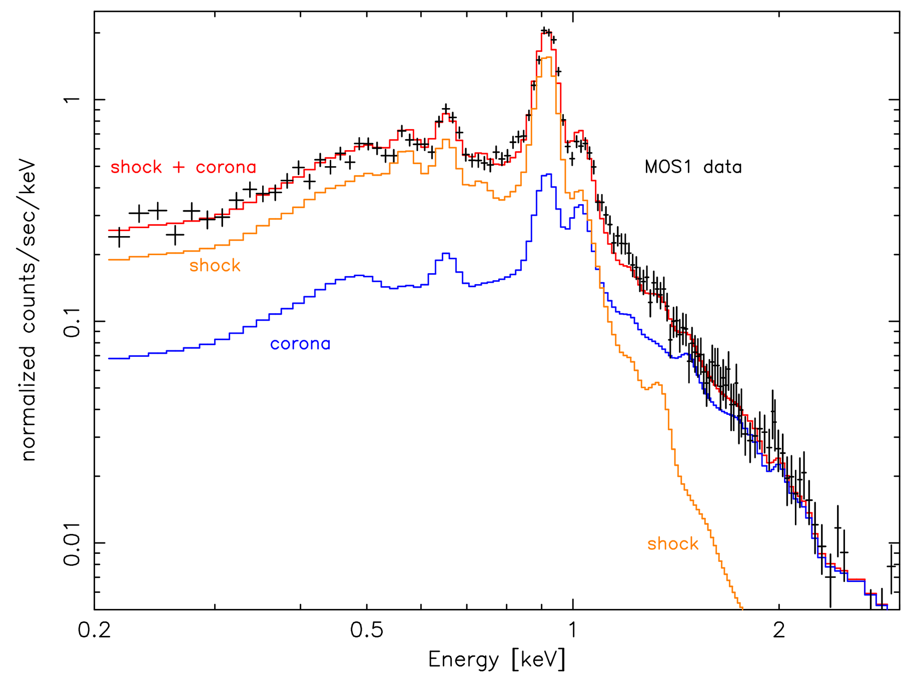

Figure 5: Low resolution EPIC spectrum of TW Hya decomposed in the coronal and accretion contribution.

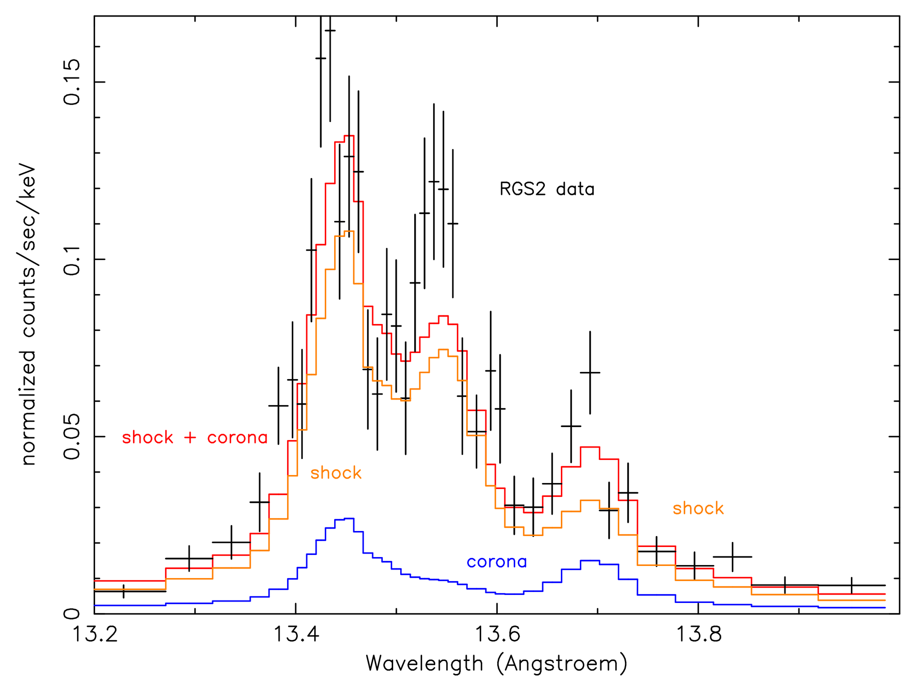

Figure 6: Emission in the He-like oxygen triplet. Only the high-density accretion component contributes to the i line.

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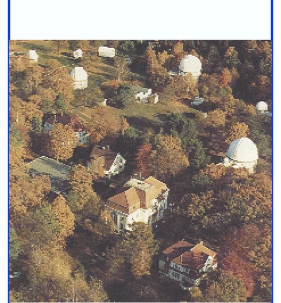

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