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Modelling the X-rays of classical T Tauri stars

The binary CTTS V4046 Sgr

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Abstract. Three classical T Tauri stars (CTTS) have so far been observed with high S/N and high resolution X-ray spectroscopy yet: TW Hya, BP Tau and V4046 Sgr. Their spectra indicate high densities and it is still a matter of some debate if they are exceptional objects or representatives of their class. V4046 Sgr is a close binary consisting of two K stars with typical signatures of CTTS. It has been observed with Chandra/HETGS for 150 ks. The helium-like triplets of Si, Ne and O are clearly detected. Using a 1-dim, stationary, non-equilibrium model of the post-shock accretion zone, the emission observed can be decomposed in accretion and coronal components. The accretion with its comparatively high densities explains unusual f/i ratios in the triplets, the coronal component explains the high energy emission at temperatures, which cannot be reached in an accretion shock.

Key words. Accretion – Methods: numerical – Stars: pre-main sequence – Stars: individual: TW Hya, V4046 Sgr – Stars: late-type – X-rays: Stars

1. Introduction

Classical T Tauri stars (CTTS) are low-mass pre-main sequence objects still actively accreting from a surrounding disk. It has been known for a long time that they are X-ray emitters (see review by Feigelson & Montmerle 1999), but only observations with high resolution gratings revealed through He-like triplet diagnostics that the emitting plasma shows unusually high densities, which cannot be interpreted as a scaled-up version of the solar corona (Kastner et al. 2002; Stelzer & Schmitt 2004; Schmitt et al. 2005; Günther et al. 2006). We follow the idea of Koenigl (1991), that the accretion proceeds along magnetically funnelled streams and the X-ray emission is produced in an accretion shock at the footpoints of the funnel, where the material impacts on the stellar surface with free-fall velocity.

In this paper we model the accretion component, add a low-density coronal component and fit the *Chandra* observations in order to obtain accretion flow parameters.

2. The model

The model is described in detail in Günther et al. (submitted to A&A), following the ideas of Shu et al. (1994). A shock develops, where the ram pressure equals the thermodynamic pressure of the surrounding stellar atmosphere (see Fig. 1). The shock is treated as a mathematical discontinuity, where the ion gas is heated according to the Rankine-Hugoniot conditions, it sets the origin of the z coordinate.

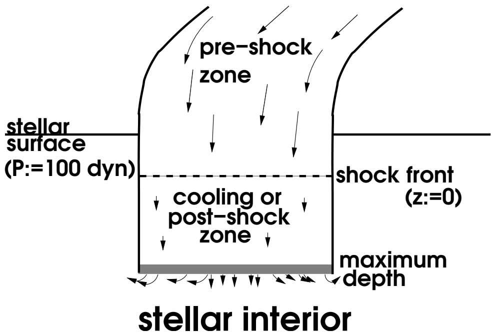

Fig. 1. A sketch of the accretion shock geometry.

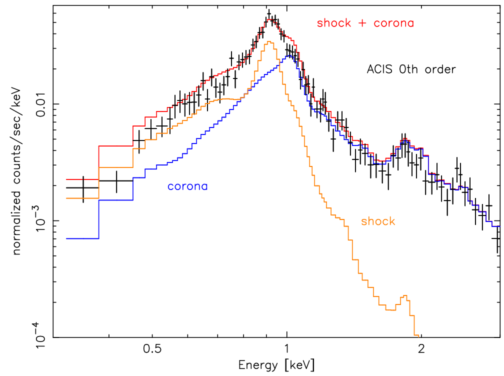

Fig. 2. CCD spectrum of V4046 Sgr with best-fit model (red/grey). The model components are the shock (orange/light grey) and the the low-density corona (blue/black).

In the post shock cooling zone we stepwise integrate the hydrodynamic and the ionisation equations in a two fluid approximation of electrons and ions under the following assumptions: No heat conduction through the boundaries or inside the cooling flow, no viscosity, both components have their own Maxwell distribution, stationarity of the problem, all gas is optically thin and the magnetic field $\boldsymbol{B}\|\boldsymbol{v}$, so it does not influence the flow. We further assume that hydrodynamics and atomic physics can be treated separately during each step. This leads to an ordinary differential equation for the ion temperature $T_{\rm ion}$ in depth z:

$$v\frac{\mathrm{d}}{\mathrm{d}z}\left(\frac{3}{2}kT_{\rm ion}\right) + vnkT_{\rm ion}\frac{\mathrm{d}}{\mathrm{d}z}\left(\frac{1}{n}\right) = -\omega_{ei} \qquad (1)$$

for the ions with number density n and bulk velocity v, where k is the Boltzmann constant. ω_{ei} describes the heat flow from the ions to the colder electrons according to Coulomb interactions. A similar relation is obtained for the electrons, containing additional terms for radiative losses. We vary the model parameters infall velocity v_0, infall density n_0 and the abundances of C, N, O, Ne, Mg, Si, S and Fe. We then use XSPEC to fit out shock and two low-density APEC components, representing the corona, with coupled abundances simultaneously to the data.

3. Results

The observation and data reduction is described in detail in Günther et al. (2006). Our best-fit results are shown in Fig. 2. The accretion shock dominates in the soft part of the spectrum and its flux rapidly falls off above 1 keV, because the infall velocity sets an upper limit on the energy per particle. The more energetic part is dominated by the corona. Fig. 3 shows the He-like Ne ɪx triplet. In purely coronal sources the forbidden line is stronger than the intercombination line. Here the high density plasma in the accretion shock emits in the i line, resulting in a f/i ratio close to 1. This density-sensitive ratio constrains the infall density, the temperature the infall velocity. From the normalisation of the shock emission the to-

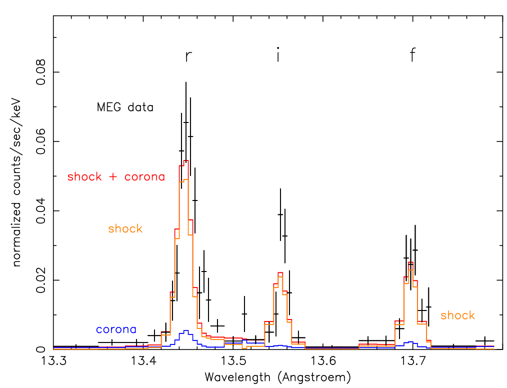

Fig. 3. Ne ɪx triplet in V4046 Sgr, see Fig. 2. Only the high density accretion shock component contributes to the intercombination line.

Table 1. Best fit parameters for the CTTS TW Hya and V4046 Sgr

Parameter	TW Hya	V4046 Sgr
v_0 [km s^{-1}]	525	535
n_0 [cm^{-3}]	10^{12}	2×10^{11}
filing factor	2×10^{-3}	1×10^{-3}
$\dot{M}$ [$M_\odot$/yr]	2×10^{-10}	3×10^{-11}
χ^2 (dof)	1.57 (577)	1.23 (1113)[a]
obs. flux (energy band 0.3-2.5 keV) in erg/cm^2/s		
shock	3.7×10^{-12}	1.2×10^{-12}
corona	2.0×10^{-12}	1.2×10^{-12}

[a]: Churazov weighting necessary because of the small number of counts per bin

tal emitting area and therefore the filling factor, defined as the ratio of spot area to stellar surface, can be estimated. We assume a distance of 83 pc (Quast et al. 2000). The resulting numbers are given in table 1 and compared to results for TW Hya from Günther et al. (submitted to A&A). V4046 Sgr is a system of two CTTS, a K7 and a K5 dwarf. As it is not resolved in our observation and the parameters of both stars are similar, we treat it in the same way as a single star. The resulting mass accretion rate is possibly split between both objects.

In general the mass accretion rates obtained by our method are surprisingly low. This is likely due to geometrical effects. In our simple 1D approach half of emission is generated upwards, but in reality photons crossing from the comparatively thin plasma in the accretion funnel into the stellar atmosphere get absorbed. This lowers the total intensity observed (see Fig. 1) and leads to an underestimation of filling factor and mass accretion rate. Because the local geometry of the accretion funnel and the size of individual spots are uncertain, it is very difficult to estimate the importance of this effect. Furthermore, recent simulations indicate that the accretion spots may be inhomogeneous with a distribution of infall velocities (Romanova et al. 2004; Gregory et al. 2006). In X-ray observations only the highest velocity regions can be probed, where the temperature is reaches a few MK. All accretion regions with infall velocities below about 450 km s^{-1} are X-ray dark. We stress that the shock takes place inside the optically thick stellar atmosphere, but still the photons can escape through the thinner cooling flow and pre-shock zone. This picture is fully consistent with the measured column densities.

4. Conclusions

Accretion shocks are an important contributor to the X-ray emission from V4046 Sgr. An detailed model of the accretion shock well explains the density sensitive line ratios. It allows to estimate the infall parameters and infer a mass accretion rate based on X-ray observations alone. In addition V4046 Sgr is found to posses a ”normal“ stellar corona.

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