LINE EMISSION FROM THE ACCRETION SHOCK IN CLASSICAL T TAUROI STARS

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**Abstract**
We present a preliminary model that seeks to reproduce the line emission from the accretion shock in Classical T Tauri Stars (CTTSs). Observationally, “transition region” lines like CIV (1550 Å), and SiIV (1400 Å) are stronger and wider in CTTSs than in WTTSs. A likely possibility is that this is due to the contribution of the accretion shock region to the emission. Here we use the Chianti database to model the shock, Cloudy to model the pre-shock and we do not assume ionization equilibrium. The model is partially successful in reproducing the SiIV/CIV ratios of some stars, but, at this point, it cannot reproduce the line ratios of semi-forbidden lines.

**Introduction**
This poster presents a preliminary model of the accretion shock of CTTSs. This is the region in which the accretion process ends. The goal of the model is to explore the contribution of the accretion shock to the observed line spectrum. Numerous high resolution spectra of CTTSs in the ultraviolet are now available (from GHRS/HST and STIS/HST) and Chandra X-Ray spectra of CTTS are now appearing in the literature. Here we will concentrate in the SiIV (1400Å) and CIV (1550Å) resonance doublets. In main-sequence low-mass stars, these lines are emitted in the transition region of the atmosphere and so they are called “transition region” (TR) lines. Our working hypothesis is that in CTTSs they are
emitted from the accretion shock region. TR lines are stronger and wider in CTTSs than in WTTSs (Ardila et al. 2002) and their luminosity is correlated with accretion rate (Johns-Krull et al. 2000).

1. Magnetospheric Accretion

The current consensus among the community is that the accretion disk is truncated close to the star by its magnetic field. A picture of the situation is in Figure 1. Material from the disk is captured by the magnetic field and produces a strong shock upon collision with the stellar surface. For typical values (a late K star about 5 Myrs old, with an accretion spot with a filling factor equal to \( \sim 0.01 \)), the incoming gas velocity is \( \sim 300 \) km/s and the density is \( \sim 10^{13} \) cm\(^{-3} \). The shocked gas cools mainly by emitting lines that are optically thin or effectively thin. For typical parameters, the most important coolants (longward of the Lyman limit) are OVI (1032 Å), CIV (1550 Å), and NV (1239 Å). Radiation from the shock heats the incoming material, creating a “pre-shock”, an HII-like region. It also heats the stellar surface creating a hot spot. In general, as we show below, the pre-shock is larger than the post-shock, and so the observed line emission is pre-shock emission that is observed through the pre-shock (Figure 2).

2. The model

Our goal is to produce a model of the accretion shock that is easy to upgrade (as atomic data become better) and easy to distribute, tailored to HST and CXO data. There have been previous attempts at modeling this region. Calvet & Gullbring (1998) present a model of the continuum emission, self-consistently calculating the heating of the stellar surface. However, they assume ionization equilibrium. Although this has little effect in the continuum emission, it affects line emission. Lamzin (1998) presents a fully self-consistent model using a reduced set of elements.

The emission from the post-shock gas is calculated using Chianti. Because the gas is fast moving, equilibrium ionization cannot be assumed. We calculate the non-equilibrium state of the gas. The result is a non-equilibrium cooling function. The emission lines responsible for the cooling are used to illuminate the pre-shock. Their effect on the pre-shock is calculated using Cloudy. In the pre-shock, the assumption of ionization equilibrium is valid. Cloudy produces the pre-shock structure and the initial ionization condition for the post-shock. From this initial conditions and the cooling function, a new post-shock structure and ionization states are calculated. This serves as input for Chianti in the next cycle.
The Magnetospheric Accretion Model

Figure 1. The Magnetospheric Accretion Model, for the idealized case of a dipolar magnetic field perfectly aligned with the stellar rotation axis.
Figure 2. Detail of the accretion shock. The top plot shows typical parameters. The bottom plot shows how radiation escapes.

- **Star** (~4000 K)
  - Cooling radiation: Heats Hot Spot & Pre-Shock
  - Continuum opacity
  - Observed Emission

- **Hot Spot**
  - ~0 km/s, $10^{15}$ cm$^3$, $10^4$ K

- **Post-Shock**
  - ~70 km/s, $4 \times 10^{13}$ cm$^3$, $10^6$ K

- **Shock Surface**
  - 10$^3$ cm

- **Pre-Shock**
  - 300 km/s, $10^{13}$ cm$^3$, $2 \times 10^4$ K

- **Funnel Flow**
  - 10$^8$ cm
Figure 3. Iteration cycle: Dark shades are program blocks, light shades are outputs/inputs.
3. Results

We produce a grid of models. Every point in the grid is parametrized by the infalling gas density and velocity, before it shocks. Figure 4 shows the resulting profiles for the pre- and post-shock, for two values. The pre-shock gas recombines at $\sim 10^8$ cm from the stellar surface. Figure 5 shows the ionization states of CIV, CV, SiIV and SiV, for 300 km/sec. Notice the substantial difference between the equilibrium and non-equilibrium states. This means that traditional differential emission analysis (which relies on the ionization equilibrium curves) is not valid in CTTSs.

The model can explain the gross features of the SiIV/CIV line ratio, as Figure 6 shows. For example, other measurements confirm that the density of the incoming gas stream for BP Tau is $\sim 10^{13}$ cm$^{-3}$. DG Tau has a very large accretion rate, which increases the density of the gas. Interestingly, for TW Hya, the ratio is 0.03 (Herczeg et al. 2002, not shown) and the infalling velocity is $\sim 500$ km/s. Our model has trouble reproducing such small ratios. For a possible explanation of this anomalous ratio see the conference paper by Stelzer in this volume.

As noted also by Lamzin (1998), the contribution of the pre-shock to the transition region flux may be considerable: for SiIV at 300 km/s, $10^{13}$ cm$^{-3}$, the pre-shock produces twice as much line flux as the post-shock. While its temperature is just $\sim 2 \times 10^4$ K, it is ionized by post-shock radiation. Our model has difficulties reproducing line ratios originated mostly in the pre-shock (Figure 7).

4. Discussion & Summary

We present here preliminary results of a model of the accretion shock, with the goal of reproducing the transition region lines observed in the UV spectra of CTTSs. The mode is successful in reproducing the observed SiIV/CIV ratio, but has trouble reproducing intercombination line ratios, which are predominately created in the pre-shock. Pre-shock sizes can be much larger than the stellar radius, and so the geometry of the accretion funnel should be taken into account.

Assuming standard coronal abundances, our model cannot reproduce the TW Hya X-ray spectrum from Kastner et al. (2002). However, there is enough energy in the accretion flow to produce the highly ionized species observed in the CXO spectrum.
Figure 4. Pre- and Post-shock temperature profiles for characteristic grid points.

100 km/sec $10^{13}$ cm$^{-3}$, Post-shock

300 km/sec $10^{15}$ cm$^{-3}$, Post-shock
Figure 5. Ionization fraction (the ratio of the atom density in the given ion to the density in all ionization states) as a function of temperature. Dashed lines are ionization equilibrium calculations, solid lines are the result of the model.
Figure 6. SiIV to CIV ratio as a function of (calculated) infalling velocity. Dots are measurements from Ardila et al. (2002). Asterisks are from Johns-Krull et al. (2000). The solid lines show the results of the model, for a range of infalling gas densities.
Figure 7. Ratios of intercombination lines. Solid: constant density. Dashed: constant velocity. The model does not work as well here (as in Figure 6), but these ratios are independent of poorly known quantities like the stellar radius. A better fit is obtained by Lamzin & Gomez de Castro (1998).
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References