A Consistent Model of the Accretion Shock Region in Classical T Tauri Stars

D. R. Ardila* and C. M. Johns-Krull†

*NASA Herschel Science Center - MS 100-22, IPAC / Caltech
1200 E California Blvd, Pasadena, CA 91125, USA
ardila@ipac.caltech.edu
†Department of Physics & Astronomy - MS 108, Rice University
6100 Main Street, Houston, TX 77005, USA
cmj@rice.edu

Abstract. We develop a consistent model of the accretion shock region in Classical T Tauri Stars (CTTSs). The initial conditions of the post-shock flow are determined by the irradiated shock precursor and the ionization state is calculated without assuming ionization equilibrium. Comparison with observations of the C IV resonance lines ($\lambda\lambda$ 1550 Å) for CTTSs indicate that the post-shock emission predicted by the model is too large, for a reasonable range of parameters. If the model is to reproduce the observations, C IV emission from CTTSs has to be dominated by pre-shock emission, for stars with moderate to large accretion rates. For stars with low accretion rates, the observations suggest a comparable contribution between the pre- and post-shock regions. These conclusions are consistent with previous results indicating that the post-shock will be buried under the stellar photosphere for moderate to large accretion rates.

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CONTEXT

Classical T Tauri Stars (CTTSs) are young, low mass stars, accreting from a circumstellar disk. Their spectra show strong excess emission over a broad range of wavelengths. These excesses result from the presence of the accretion disk and its interaction with the stellar magnetic field. In particular, the excess line emission at optical wavelengths has been successfully modeled (e.g. [10]) as being due to the presence of gas captured in the extended magnetosphere. The continuum excess is believed to be primarily due to heating of the stellar photosphere by the same gas as it falls into the star [2].

Line excesses are also observed at UV wavelengths, and the observational problem is conceptually similar to the optical one, although the shorter wavelengths imply that the lines trace higher energy processes. As in the optical, surface fluxes are much larger than expected from a naked atmosphere. [7] have showed that the surface flux in the C IV resonant lines ($\lambda\lambda$ 1550 Å) can be as much as an order of magnitude larger than the largest flux observed in Weak T Tauri stars (WTTs), main sequence dwarfs, or RS CVn stars. They have also showed that the excess flux in the lines is strongly correlated with accretion rate, suggesting that the lines are powered by the accretion process.

The diagnostic power of these observations is limited due to the lack of complete, self-consistent models of the region. We have developed such a model, with the goal of

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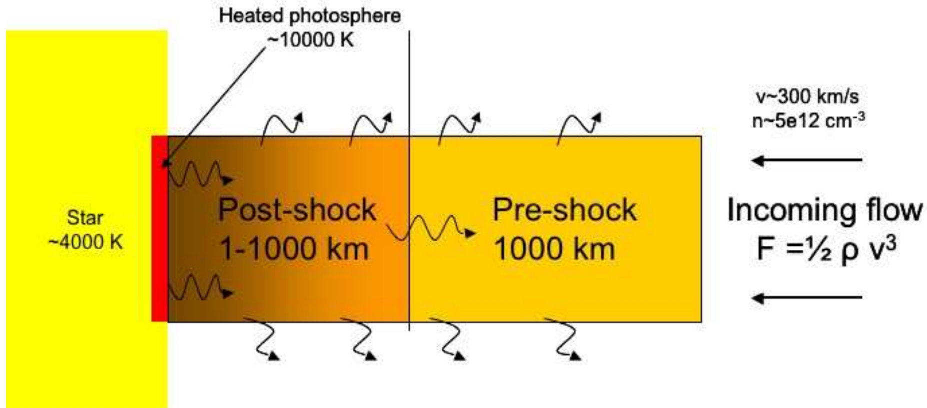

FIGURE 1. Structure of the shock region. Typical post-shock temperatures range from 1 to 2×10^6 K. Pre-shock temperatures are $\sim 10^4$K.

understanding the contribution of the accretion shock region to the observed lines. In this poster, we focus primarily in explaining the UV lines observations from [7]. A more complete study of the outstanding problems can be found in [1].

MODEL CHARACTERISTICS

The flow of the accreting gas into the stellar photosphere is supersonic and produces a strong radiative shock close to the star. Some of the radiation from this shock is directed upstream, creating a radiative precursor (the "pre-shock"). The rest is directed downstream and heats the stellar photosphere. In principle, the observed spectrum will be a combination of four different regions: (1) Star; (2) Heated photosphere; (3) Pre-shock radiation; (4) Post-shock radiation (See Figure 1).

To determine the relative contributions of all the regions, we solve the hydrodynamic equations in the post-shock for the density and temperature in the region. With these, we calculate the resulting spectrum using the Chianti database [9]. The light emitted by the post-shock illuminates the pre-shock creating a photoionized region whose structure is calculated using Cloudy [4].

The model grid is parametrized by the incoming flow velocity and density. For each of these pairs, the model predicts the size of the pre- and post-shocks, as well as the surface flux from each region.

Our formalism does not assume ionization equilibrium for the post-shock, with the consequence that highly ionized species are formed at lower temperatures that in static plasmas. In addition, it differs from previous published models [8, 2, 5] in that it explicitly considers the fact that the post-shock radiation alters the ionization state of the gas crossing the shock surface. This results in shorter post-shock sizes and larger emission in the transition region lines.

As a sanity check, we adapt our model to match the assumptions from previously published works. We can reproduce the C IV fluxes predicted by [8], which focuses on lower density accretion flows. By ignoring the initial conditions imposed by the ionized

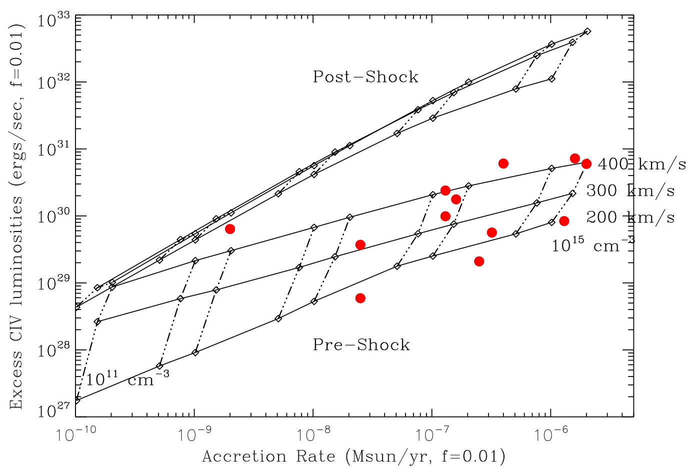

FIGURE 2. Observations and model predictions for the relationship between C IV and accretion rate

pre-shock, our model can reproduce the X-ray G (*f/i*) and R ((*f*+*i*)/*r*) ratios for N V, O VII, and Ne IX, from [5]. Our results for the structure of the pre- and post-shock are roughly consistent with those from [2].

THE C IV LUMINOSITY

Figure 2 shows (red dots) the excess C IV luminosities for a group of CTTSs, taken from [7]. These are stars for which the extinction, accretion rate, stellar radius, and distance are considered well known. IUE measurements yield the C IV excess luminosity (calculated by subtracting the expected intrinsic C IV luminosity). We have added the measurement for TW Hya (with accretion rate 2×10^{-9} M_{sun}/yr. See [6]). Note that this measurement does not obey the correlation between accretion rate and C IV luminosity derived by [7]. Its C IV emission is too big for its accretion rate.

Figure 2 also shows the predictions from our model, assuming an accretion filling factor f of 1% [2]. Densities for the infalling gas range from 10^{11} cm^{-3} to 10^{15} cm^{-3}, while velocities range from 200 km/s to 400 km/s.

The pre-shock region (of the order of thousands of kilometers in size) is larger than the post-shock region (with sizes that can range from tens to thousands of kilometers), but it is optically thick in C IV compared to the mostly optically thin post-shock region. As the density decreases, the post-shock emission decreases faster than the pre-shock emission. At accretion rates of few parts $\sim 10^{-10}$ Msun/yr, the contribution of pre and post-shock regions to the observed line emission becomes comparable.

A precise comparison with observations would require fixing a number of poorly known geometric parameters (accretion filling factor, inclination to the line of sight, etc). However, it is clear that the post-shock emission derived from our model is too large compared to the observations of all stars except TW Hya, while the pre-shock emission seems apropiate for all stars except TW Hya.

According to [3], the ram pressure of the incoming flow is large enough to bury the shock for all but the lowest accretion rates. Our results are consistent with this idea. For moderate to high accretion rates, the shock should be buried, and only the pre-shock emission will be observed. For low accretion rates emission from the shock will be visible. The exact meaning of "low" and "moderate to high" accretion rates depend on the pressure structure of the star.

This picture predicts that other low accretion rate stars like TW Hya will not obey the correlation derived by [7], because the post-shock will not be buried and so it will contribute substantially to the C IV emission. In support of this idea, low resolution spectroscopic X-ray observations show that stars with moderate accretion rate do not present the soft X-ray exceess[11] expected from the existence of the post-shock.

OPEN QUESTIONS

Resolved observations of C IV and other "transition region" lines for a handful of CTTSs, reveal that the lines are broad ($\sim$300 km/s) and present a diversity of centroids, from very blueshifted (like DG Tau) to moderately redshifted (like DR Tau)[1]. If the line emission from stars with moderate accretion rates is dominated by pre-shock emission (with flow velocities of a few hundred km/s towards the star), why are the lines not redshifted? We will explore this issue in an upcoming publication.

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