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Accretion Processes in T Tauri Stars: GHRS Observations

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Abstract. We have performed observations of eight classical and one weak T Tauri Star, using the GHRS instrument on board of HST. We observe the Si IV (1400 Å), C IV (1550 Å), and Mg II (2800 Å) resonance doublets, and numerous H_2 lines. Here we discuss the observational characteristics of these lines.

1. Introduction

Classical T Tauri Stars (CTTS) are young pre-main sequence stars surrounded by an accretion disk. In the current magnetospheric accretion model, the disk is truncated close to the star by the stellar magnetic field. Material from the disk is channeled by the field and slides down the gravitational potential of the star. It is believed that material in this accretion funnel may be responsible for the strong emission lines observed in the optical range of CTTS (Muzerolle, Calvet, & Hartmann 2001). Close to the stellar surface, the gas shocks and may reach temperatures of 10^6 K. Densities in this region are of the order of $\sim 10^{13}$ cm^{-3}. The temperature then decreases until the stellar photosphere is reached (Calvet & Gullbring 1998). Given the characteristics of the accretion flow, it should be possible to observe Mg II emission (at 2800 Å, which in the Sun forms at ~ 7000 K) coming from the accretion funnel, and Si IV (1400 Å) and C IV (1550 Å), coming from the shock region (both lines are formed at $\sim 10^5$ K). All these lines are resonant, which makes their analysis easier than that of the Balmer lines. The hot lines provide a unique window into the very compact region of the shock itself.

In this work, we present observations of ultraviolet emission lines in eight CTTS (BP Tau, T Tau, DF Tau, RW Aur, DG Tau, DR Tau, RY Tau, RU Lup) and one Weak T Tauri Star (WTTS, HBC 388, also known as NTTS 042417+1744). The CTTS are medium and high accretion rate systems, with a range of masses and inclinations. The observations were performed with the Goddard High Resolution Spectrograph (GHRS) which flew on board of HST. The resolving power is 20000 at 1500 Å, and the aperture of the spectrograph

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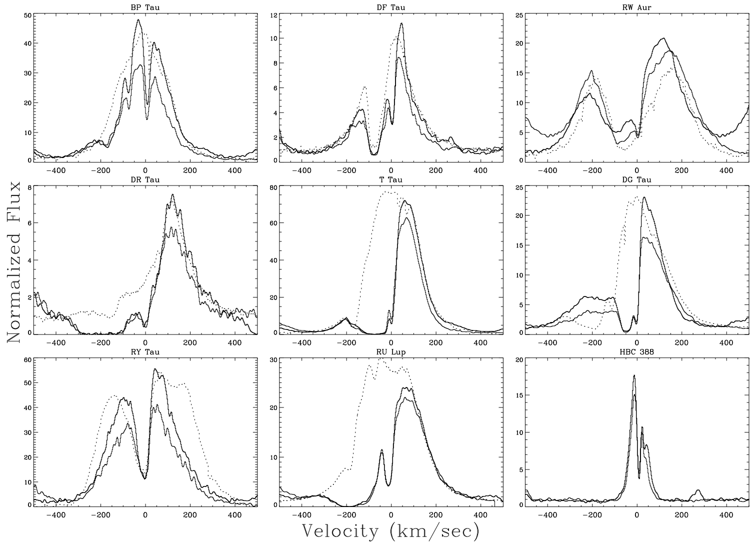

Figure 1. The solid thick (thin) line is the Mg II k (h) line. H_α is shown dotted. The UV and optical observations are simultaneous (within 24 hrs.) for BP Tau, DR Tau, RW Aur, and DF Tau. The rest of the optical observations have been provided by Silvia Alencar and Celso Batalha. No H_α observations are shown for HBC 388.

is $\sim 2''$. The observations that we present here are based on spectral ranges 40 Å wide centered on 1400, 1550, and 2800 Å. These ranges contain the Si IV, C IV, and Mg II resonance doublets. In addition, a large amount of molecular hydrogen lines are present in the spectra.

This work seeks to explore the following questions: What can the Mg II lines tell us about line formation in the funnel flow? As the 2800 Å Mg II lines are resonant transitions, they are very sensitive to the outflow. What can they tell us about the wind? Where does the accretion shock line emission come from? There are two possibilities here: the radiative precursor of the shock and the post-shock. There is abundant number of H_2 lines. Where does H_2 come from? How is it excited?

2. The Funnel Flow and the Outflow

Figure 1 shows the resonance doublet of Mg II, compared with H_α. As can be seen, the lines are wide (FWHM$\sim$250 to 300 km s^{-1}) in most cases. The WTTS lines have FWHM$\sim$70 km s^{-1}. This suggests that, in these lines as in the Balmer lines, the emission is the result of accretion processes and not the stellar chromosphere.

The Mg II have a narrow central absorption, due to non-LTE processes (it is wider than the usual ISM absorption), and a wide blueshifted absorption indicating the presence of an outflow. In some of the stars this absorption reaches below the continuum, which suggests that it is indeed a true absorption. The morphology of the whole line is similar in Mg II and H_α, except for RY Tau. In

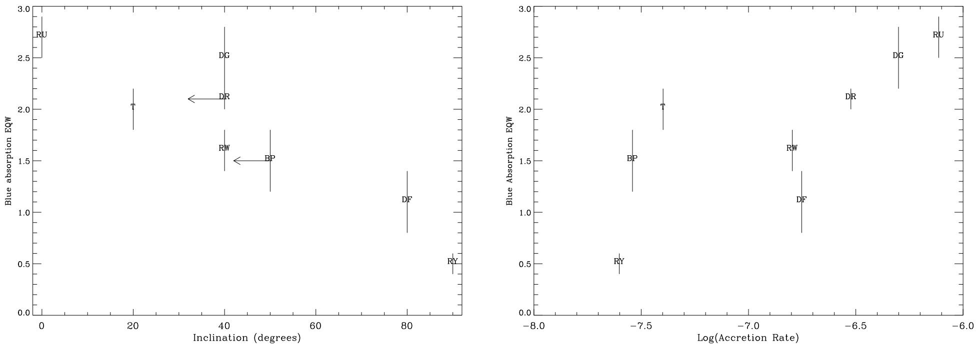

Figure 2. Left: EQW of wind absorption (in Å) versus stellar inclination (in degrees). The EQW has been corrected for the narrow central absorption in all stars. For the stars with double wind components, the EQW is taken over both. Upper limits in the inclination are indicated by arrows. Right: Relationship between the EQW of the k line wind absorption (in Å) and the accretion rate (in $M_{\odot}/yr$). The accretion rates have been taken from Calvet & Gullbring (1998), Gullbring et al. (2000), and, after reducing them by an order of magnitude, from Hartigan, Edwards, & Ghandour (1995).

Mg II the blueshifted absorptions are deeper and wider than in H_{α}, as expected for a resonant transition sampling a relatively cold wind. This indicates that both lines are tracing the same outflow.

It has been suggested that the linear Stark effect, the pressure broadening mechanism that affects only the hydrogen lines, is responsible for the large width observed in CTTS for members of the Balmer series (Muzzerole et al. 2001). With the exception of RY Tau, the Mg II line wings have the same shape as those of H_{α}, which shows that the process responsible for making the lines so broad, cannot be atom dependent, i.e., it cannot be linear Stark effect. Perhaps (supersonic) turbulence is responsible for these large widths. It has also been suggested that the wings in some CTTS maybe emitted in the outflow (Beristain, Edwards, & Kwan, 2001).

If we take the more traditional idea that all the emission is due to material in the accretion funnel and that the outflow contributes only to the absorption, the equivalent width (EQW) of the blueshifted absorption should depend only on the characteristics of this outflow. In this case the EQW measures simultaneously the velocity and the density of the absorption. In Figure 2, we show that a correlation exists between the EQW and the stellar inclination (left panel), in the sense that face on stars tend to have blueshifted absorptions with larger EQW. The right panel shows that a weak correlation is present also between EQW and accretion rate.

While the correlations in both figures are very weak, it should be noted that for stars with the same inclination (RW Aur, DR Tau, and DG Tau), the star with the highest accretion rate has the highest EQW. Similarly, for stars with the same accretion rate, the one with the most pole-on star has the highest EQW. This suggest that the optical depth of the wind absorption increases as

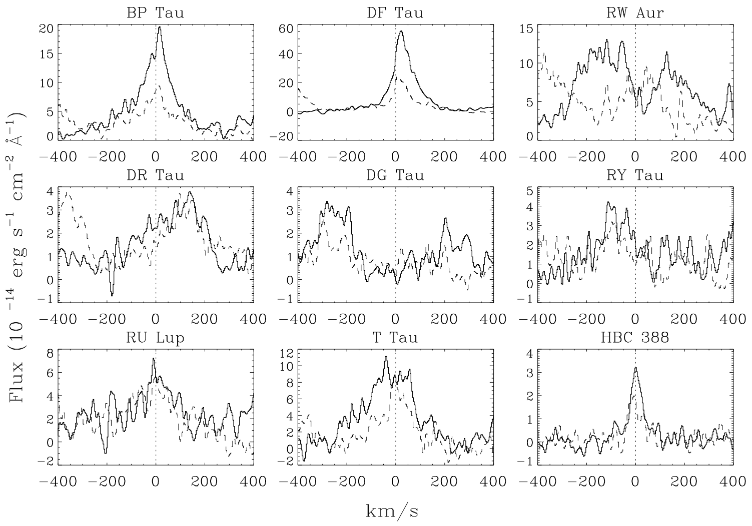

Figure 3. The solid thick (dashed thin) line is the thicker (thinner) member of the C IV doublet.

the line-of-sight becomes parallel to the rotation axis of the star, and it is larger for larger accretion rates. In other words, the outflow is not spherical.

3. The Hot Lines

Figure 3 shows the C IV resonance doublet. The Si IV doublet (not shown) has the same shape. The lines of the CTTS have FWHM ranging from ~100 to 200 km s^{-1}. The weakness and small width of the lines in HBC 388 imply that the emission in the CTTS is due to accretion processes.

In general, C IV is optically thin, while Si IV is not (the exception is DR Tau, for which C IV is not optically thin). This is difficult to understand, given that the lines come from the optically thin region of the shock. Perhaps, as suggested by Lamzin (1998), the formation of these lines occur at very low temperatures ($\sim 10^4$ K) in the post-shock, where the flow is becoming optically thick to its own cooling radiation. However, in this case it is difficult to understand the large widths of the lines (thermal broadening implies FWHM of only ~60 km s^{-1}).

It is also difficult to understand the centroids of the lines: some lines are centered (as expected if the formation occurs in a slow moving flow close to the stellar surface), redshifted (as expected if the formation occurs in a fast moving flow, like that of the pre-shock), and blueshifted (which require special flow configurations to be explained, as modeled by Lamzin 2000).

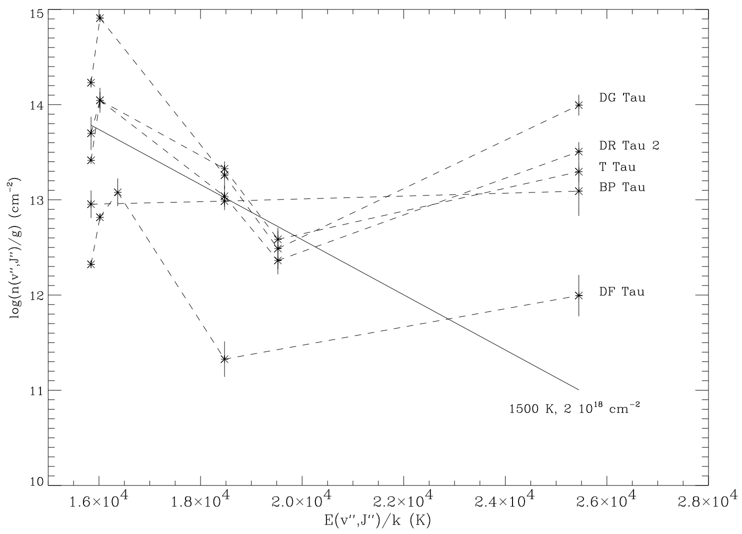

Figure 4. Exciting populations of H_2 for a selected sample of stars. The populations have been obtained assuming that the H_2 is surrounding the stellar surface and intercepts all the Lyα flux. These very uncertain assumptions produce large systematic errors in the ordinate, the column densities of each level. However, the ratio between two levels depends only on the shape of the exciting agent. If the exciting levels were in thermal equilibrium we would obtain a straight line. For comparison, we include the line corresponding to a 1500 K thermal distribution with a total H_2 column of 2 10^{18} cm^{-2}.

4. Molecular Hydrogen

Large number of H_2 lines are observed. All belong to the Lyman band. They are narrow (40 km s^{-1} in average), but wider that the instrumental resolution, which suggests that they come from an extended region, as has been observed for T Tau (Brown et al. 1981). All are slightly blueshifted ($\sim$ 10 km s^{-1} in average). Here it is useful to remember that the large aperture of the spectrograph will produce systematic centering errors in the velocity of $\pm$20 km s^{-1}. In this light, the blueshifts are not significant. However, the fact that the lines in all the stars are shifted to the blue suggests that the observed H_2 emission comes from an outflow.

We believe the lines are due to Ly$_\alpha$ fluorescence, because all the observed transitions can be traced back to an exciting transition within a 1000 km s^{-1} of this line. The observed exciting transitions are (v";J"): 2;0, 2;1, 2;2, 2;5, 2;6, and 1;13. Any model that seeks to explain these observations should explain also how is it possible to excite H_2 to such higher levels.

Assuming that the Ly$_\alpha$ can be modeled as a Gaussian with a FWHM=680 km s^{-1} (as suggested by TW Hya observations, see Herczeg et al. 2001), it is possible to obtain the populations of H_2 in each of the exciting levels. This is shown in Figure 4. As the figure indicates, the populations are not thermal, which suggests that the agent responsible for their distribution is irradiation and not shocks (which would produce a thermal distribution).

5. Conclusions

• Comparison between Mg II and H_α shows that the width of these lines cannot be due (as has been argued) to atom dependent effects like the linear Stark effect.
• We observe evidence of a non-spherical wind. Its optical depth increases with increasing accretion rate and decreasing inclination.
• Strong C IV and Si IV lines are observed. C IV tend to be optically thin while Si IV tends to be optically thick. This stands in contrast with models of the accretion shock that predict that both lines should be optically thin. Perhaps the emission comes from the bottom of the shocked gas, where the material is becoming optically thick to its own cooling radiation. The widths and centroids of the hot lines are difficult to understand in terms of the accretion model. The lines are wider than expected given their formation temperature and a wide array of centroids are observed, when they should be mostly redshifted.
• A large number of H_2 lines are observed. All belong to the Lyman band of molecular hydrogen and we believe that they are the result of fluorescence by Ly_α. The exciting levels have energies higher than those corresponding to v"=2 and do not have a thermal distribution.

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