X-rays from Classical T Tauri Stars: Coronae or Accretion Shocks ?

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Classical T Tauri Stars (cTTS) are young stars still possessing an accretion disk. cTTS are found to produce strong X-ray emission and the origin of the observed X-rays can be attributed either to a dynamo-induced corona, the stars being very young and rotating very fast, or to an accretion shock. If the latter has a significant effect over the former, one expects to see different spectral signatures in high-resolution spectra of cTTS compared to stellar coronae without accretion disks. The most prominent and X-ray strongest cTTS is TW Hya, and *Chandra* HETGS observations showed that the He-like f/i-ratios are the lowest measured in all stellar coronae, suggesting an accretion shock as the origin of the observed X-ray emission. However, He-like triplets are affected by UV emission that can produce low f/i-ratios in the absence of any high densities. Schmitt & Ness (2005) presented an additional indicator for high densities, the ratio Fe XVII $\lambda\lambda$17.10/17.05, which is, once more, the lowest among all stellar coronae. In this paper we present a careful examination of all measurements providing density diagnostics of cTTS in an effort to determine to what extent X-ray emission from an accretion shock influences the overall X-ray emission from cTTS. We conclude that progress can be made only with a lot more sensitive instruments with at least the same high spectral resolution as provided by *Chandra* and *XMM-Newton* gratings in order to assess a larger sample of suitable stars.

1. Introduction

T Tauri stars are pre-main sequence (PMS) late-type stars, which come in two flavors: "Classical" T Tauri stars (cTTS) are thought to be surrounded by accreting disks as evidenced by IR and UV excesses, while no signs for the presence of (accreting) disks are found in so-called "weak line" T Tauri stars. Both types of TTS are rapid rotators and vigorous X-ray emitters (Feigelson & Montmerle 1999; 3) and follow rotation-activity connection expectations, if their X-ray emission is interpreted as scaled-up solar-type activity. Because of fast rotation the coronae of young stars ought to be quite X-ray luminous. However, for cTTS an additional source of X-ray emission through accretion is available: the currently favored accretion models of cTTS envisage mass infall occurring along magnetic accretion funnels and the material is accreted essentially at free-fall velocities. Upon hitting the stellar surface, a strong shock is formed, converting the kinetic bulk energy into thermal energy observable at X-ray wavelengths. Detailed models of the accretion shock region by Günther et al. (submitted to A&A) concentrate on evidence for and against emission from an accretion shock versus coronal emission. X-ray production through accretion is expected to lead to significant differences in X-ray emission levels, to significant variability, and to differences in the spectral properties of the X-ray emission. These spectral characteristics show up in lines from semi-forbidden transitions of lower temperature high-density plasma as demonstrated from *Chandra* and *XMM-Newton* grating spectra, specifically in the two He-like f/i line ratios of O VII and Ne IX, which are the most prominent density tracers in the soft X-ray range. These ratios are anomalously low in the two cTTS TW Hya (Kastner et al. 2002; Stelzer & Schmitt 2004; 6; 12) and BP Tau (Schmitt et al. 2005; 11); in contrast, in a large (n> 30) survey of stellar coronae not a single such low ratio was found (Fig. 1 and Ness et al. 2004; 8). Also, the ratio of Fe XVII $\lambda\lambda$17.10/17.05 was found to be lower in TW Hya than in any other stellar corona (Ness & Schmitt 2005; 10), again suggesting high densities and an accretion shock as the origin of the observed emission. Finally, the line ratios of O VIII and Ne X Lyβ/Lyα, sensitive to resonant line scattering, were shown to be consistent (to within the errors) with the optically thin case. As a consequence the measured high levels of volume emission measure (VEM$\propto n_e \tau A$) again require

high densities (n_e), given the available emission area $A = 4\pi R_\star^2$ (Ness & Schmitt 2005).
Processes other than accretion may also contribute, but no quantitative models are available as to what emission levels can be expected. Here we only deal with the aspect of high densities that are expected from accretion. We specifically discuss the reliability of each density diagnostics suggesting a high coronal density for TW Hya. We can rule out any UV contamination to be responsible for a depression of the He-like f/i ratios of O VII and Ne IX. The ratio of Fe XVII lines is different in the separate spectra from the two dispersion directions, and we need to prove that co-adding the two spectra is statistically correct.

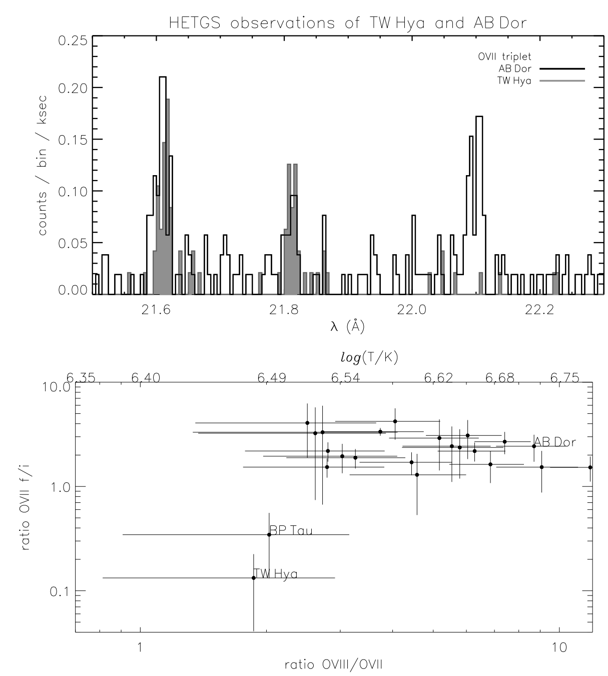

Figure 1. The O VII triplet of TW Hya differs from that of later stellar coronae. **Top**: In comparison to AB Dor (similar spectral type) the count rate in the i-line (21.8 Å) is the same, while no counts in the f-line (22.1 Å) are found. **Bottom**: The average temperature (derived from the ratio O VIII/O VII) is much lower in TW Hya than in AB Dor. A similarly low f/i ratio is only found in the RGS spectrum of another cTTS, BP Tau, but in no stellar corona.

2. He-like ratios

The He-like triplet density diagnostics utilize transitions between excited states with different radiative de-excitation probabilities to the ground $1s^2\,{}^1S_0$. The forbidden line f ($1s2s\,{}^3S$) has a low radiative de-excitation probability, while the intercombination line i ($1s2p\,{}^3P$) has a higher radiative de-excitation probability. Therefore, in a high-density plasma, collisional excitations from $2s\,{}^3S$ to $2p\,{}^3P$ depopulate the upper level of the forbidden line and, instead, populate the upper level of the intercombination line, leading to a decreasing f/i line ratio with increasing density. The dependence of line flux ratio with density has been parameterized by Gabriel & Jordan (1969; 4), who also included effects arising from radiative depopulations from photons in an external, say photospheric, radiation field. Gabriel & Jordan (1969) specifically introduce the radiation parameter ϕ/ϕ_c, which influences the f/i ratio in the same fashion as the density in units of the critical density (n_e/N_c, where the critical density is the density at which the ratio f/i is reduced to half the low-density limit). This radiation parameter can be determined from the spectral energy density u_λ at the wavelength triggering $2s\,{}^3S$–$2p\,{}^3P$ (Blumenthal et al. 1972; 1). We follow the recipe by Ness et al. (2003; 9) to convert UV measurements at the respective wavelengths for O VII (1630 Å) and for Ne IX (1266 Å) into the parameter ϕ/ϕ_c using fluxes derived from Hubble Space Telescope (HST) spectra introduced by Herczeg et al. (2002; 5). The flux level at 1630 Å is $< 10^{-13}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,Å^{-1}}$, that at 1266 Å is $< 5 \times 10^{-14}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,Å^{-1}}$. We now assume that this flux is produced by two separate blackbodies with temperatures chosen to produce the respective measured flux values. We also make the conservative assumption that the affected X-ray plasma is in the immediate vicinity of the UV emission, i.e., we use a dilution factor 0.5[1]. In Fig. 2 we show two blackbody spectra with temperatures 6700 K and 7500 K, and it can be seen that the flux level at 1266 Å is reproduced by the 7500-K model and the flux at 1630 Å by the 6700-K model. We therefore treat these temperatures as radiation temperatures and convert these into the parameter ϕ/ϕ_c according to Ness et al. (2003). In Fig. 3 we show the f/i ratio as a function of density in the non-irradiated and the UV-illuminated form. Clearly the radiation temperatures of 6700 K for O VII and 7500 K for Ne IX cannot account for the measured low values of f/i, and thus high densities are the only plausible explanation. However, the assumption

[1]Half the flux is emitted back to the star, away from the X-ray plasma

of the fluxes measured at 1630 Å and at 1266 Å to originate from uniform blackbody radiation may be too simplistic. As we are dealing with an accretion shock, the radiation may originate from a compact and possibly hotter region and Drake (2005; 2) proposes that this may lead to a stronger influence, but he does not provide a quantitative model. Such a detailed model would have to include an eventually buried shock, where the observed UV emission is produced. Obviously, a rather high radiation field would have to be produced to avoid the conclusion of high density.

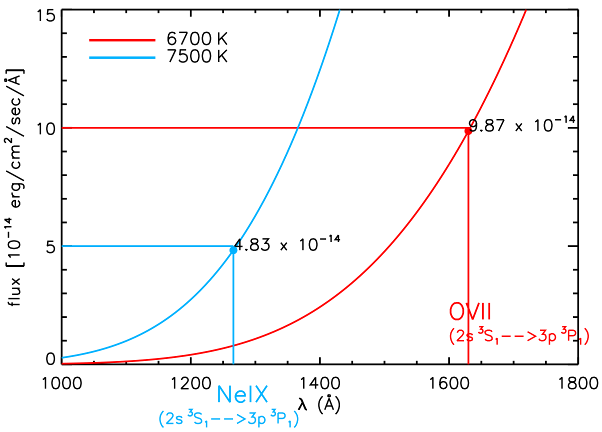

Figure 2. Blackbody spectra with temperatures 6700 K (red) and with 7500 K (blue). The fluxes measured for TW Hya at 1266 Å and at 1630 Å are reproduced by these models and the respective temperatures can be regarded as radiation temperatures triggering the transition between the He-like 1s2s ^{3}S–1s2p ^{3}P states.

3. Fe XVII ratio

The ratio of Fe XVII $\lambda\lambda$17.10/17.05 has been suspected to be a good density tracer by Mauche et al. (2001; 7), when they found the 17.10-Å to be absent, relative to a clear detection of the 17.05-Å line in the *Chandra* HETG spectrum of the intermediate polar EX Hya. In stellar coronae this line ratio is always found to be of order of unity, only in TW Hya a lower value was found (Ness & Schmitt 2005). Unfortunately, the atomic physics of Fe XVII is not (yet) well enough explored to convert the measured ratio into a density, because the upper levels are mixed and interactions with adjacent ionization stages make (otherwise valid) simplifying assumptions invalid. In addition to these theoretical issues there is a practical problem with the Fe XVII $\lambda\lambda$17.10/17.05 measurement in TW Hya. In the analysis of grating spectra it is customary to co-add the two dispersion orders to achieve higher signal-to-noise, however, a much stronger case can be made if any finding from the co-added spectrum is supported by the two separate independent spectra that can be extracted from *Chandra* HETG observations. For TW Hya this is unfortunately not true. In Fig. 4 we show the MEG spectra extracted from the two dispersion orders (dubbed plus and minus orders). In the plus order the 17.10-Å line is not detected, but the effective areas are a factor $\sim$ 3 smaller on the plus side (above 15.3 Å), and all lines are consequently measured with fewer counts. The detection limit is higher, thus, weaker lines are not detected (e.g. at 16.78 Å). The plus order alone can thus not be used for any quantitative analysis of the $\lambda\lambda$17.10/17.05-Å ratio. When extracting the ratio only from the minus side (0.73 $\pm$ 0.23), the resulting error is too large to conclude a significant deviation from the coronal measurements. The only way to infer reliable results is by co-adding both spectra and carefully checking whether the results from the summed spectrum are statistically correct.

In Fig. 5 we show an empirical study of measurements of the lines at 17.05 Å and at 17.10 Å from the plus and minus sides of various stellar coronae with different exposure times and intrinsic line fluxes, covering a large range of statistical quality. For the stars with larger photon fluxes the measured values obtained from the separate

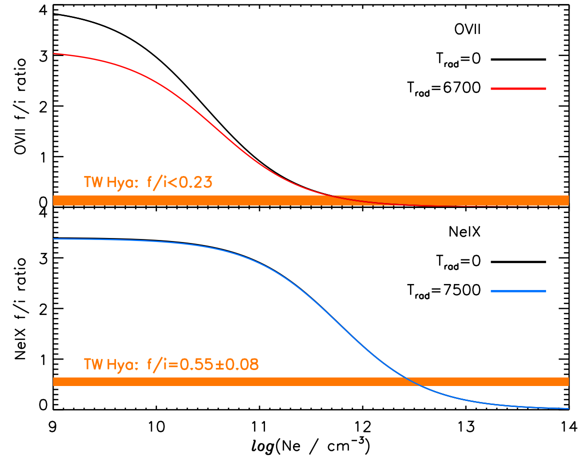

Figure 3. Change of f/i ratio with density for O VII (top) and Ne IX (bottom) with and without the measured radiation temperatures. The measured f/i ratios are marked within their 1-σ errors with light shades, and it is clear that the density measurements are not affected by UV radiation.

spectra agree very well with each other, but for the observations with smaller photon fluxes the plus order can only measure upper limits in both lines, while the minus order can still constrain the fluxes. This is easily explained by the fact that the weaker lines simply fall below the detection limit on the plus side before they do on the minus side. There are two ways to increase the signal-to-noise, one is to use longer exposure times, while the other is to use instruments with larger effective area, which can be simply achieved by co-adding the counts in both orders. Combined fluxes are thus obtained from

$$F_{\rm coadd} = \frac{{\rm counts}_+ + {\rm counts}_-}{({\rm Aeff}_+ + {\rm Aeff}_-)\Delta t}\,, \qquad (1)$$

with counts_+ and counts_- being the count spectra on the plus and minus sides, respectively, Δt the exposure time, and Aeff_+ and Aeff_- the effective areas on the plus and minus orders, respectively. This is equivalent to the effective-area-weighted mean of the fluxes F_+ and F_-, calculated from the separate spectra, i.e.,

$$\bar{F}_{\rm Aweight} = \frac{{\rm Aeff}_+ F_+ + {\rm Aeff}_- F_-}{{\rm Aeff}_+ + {\rm Aeff}_-} = F_{\rm coadd}\,. \qquad (2)$$

The effective-area-weighted average is superior over separate line measurements averaged with equal weight, $F_{\rm equal} = 0.5(\frac{{\rm counts}_+}{{\rm Aeff}_+\Delta t} + \frac{{\rm counts}_-}{{\rm Aeff}_-\Delta t})$, as the spectrum with lower effective area (in our case the plus side) has to contribute with less weight, because this measurement is less reliable. If we define the ratio of effective areas n as $\mathrm{Aeff}_- = n{*}\mathrm{Aeff}_+$ and the ratio of measured counts m as $\mathrm{counts}_- = m * \mathrm{counts}_+$ one can calculate the ratio of fluxes averaged with the two different approaches in terms of the ratios n and m as

$$\frac{F_{\rm Aweight}}{F_{\rm equal}} = 2\frac{1+m}{1+n}\frac{n}{n+m}\;. \qquad (3)$$

In Fig. 6 we illustrate the difference between the two ways of inferring average fluxes from the two spectra. In cases of identical effective areas ($n = 1$) both methods result in the same average fluxes. In cases of different effective areas, the two approaches are only identical if the number of counts scales exactly with the ratio of effective area ($n = m$). In all other cases, deviations up to 40 per cent can result and the effective-area-weighted average has to be used.

For the case of TW Hya this little excursion into photon statistics shows that there is no better way to draw any further conclusions from the existing data. The only way to obtain more information is to observe longer or to wait for a better instrument with larger effective area at the same spectral resolution.

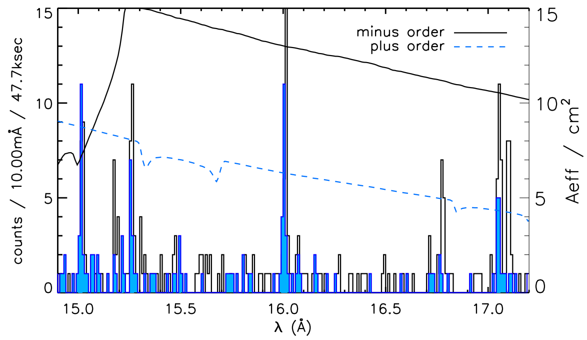

Figure 4. Comparison of plus (light blue shaded) and minus (black) dispersion orders. The number of counts is much lower in the plus order, but the effective areas (solid and dashed lines) are also smaller. The low S/N leads to non-detections of the weaker lines.

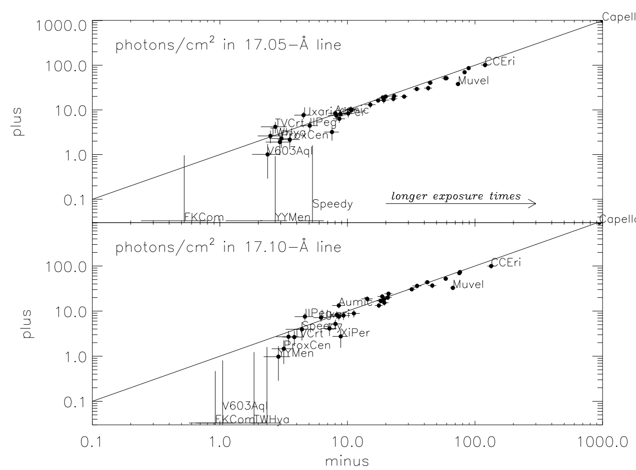

Figure 5. Comparison of line measurements of plus and minus orders for a large sample of stars. We plot photons/cm^2 to illustrate cases of good and poor photon statistics. The solid line guides the eye towards best agreement between measured line fluxes.

4. Fe XVII with RGS

The *XMM-Newton* archive contains a 28-ksec observation of TW Hya (ObsID 0112880201), which we analyzed to look for support of the results obtained with *Chandra*. These data have

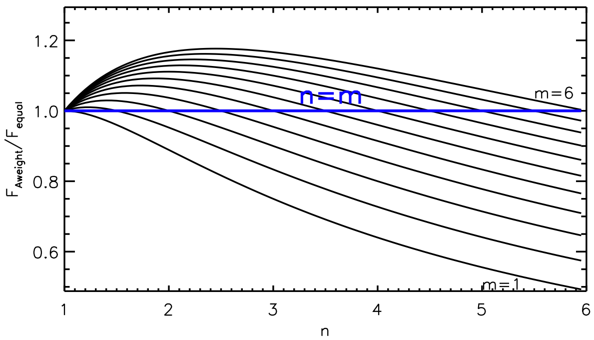

Figure 6. Ratio of photon fluxes obtained from two separate measurements weighted with individual effective areas ($F_{Aweight}$), and using the separate fluxes, equally weighted with 0.5 each (F_{equal}). If the ratio of measured counts (m) is the same as the ratio of effective areas (n), then the same photon fluxes are obtained.

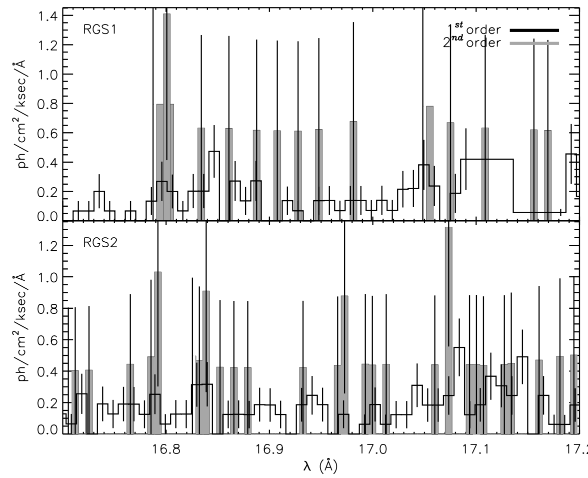

Figure 7. The RGS observations of TW Hya. The Fe XVII lines are not detected with sufficient signal (second order) or spectral resolution (first order) to find support for the *Chandra* observations.

previously been analyzed by Stelzer & Schmitt (2004; 12), who report clear evidence for a very low f/i ratio in the O VII triplett, thus confirming the previous findings by *Chandra* (Kastner et al. 2002; 6). We now focus on the Fe XVII lines. Since the RGS resolution is insufficient to resolve the Fe XVII lines at 17.05 Å and at 17.10 Å, we also extract the second dispersion order data, which have a factor two higher spectral resolution, however with considerably reduced sensitivity (between factors of four for RGS2 and five for RGS1). In Fig. 7 we show the RGS1 and RGS2 spectra in first and second dispersion orders in the range around these lines. The RGS1 has a chip gap at the wavelength of the 17.10-Å line in first order, but the RGS2 detects the lines. As already mentioned, the spectral resolution in the first-order spectra is insufficient to establish any supporting evidence of a low ratio $\lambda\lambda$17.10/17.05. In the second order not enough photons are recorded in order to arrive at any conclusions. In the RGS2 one bin contains an excess in counts at 17.05 Å, which would support our results from *Chandra*, but obviously this is by no means significant and must be discarded from any further considerations.

5. Conclusions

In stellar coronae average densities are rarely higher than $10^{12}\,\mathrm{cm}^{-3}$, and in many cases where only low-density limits in the He-like f/i ratios are measured (Ness et al. 2004; 8). Only the two cTTS TW Hya and BP Tau have been measured with significantly lower f/i ratios than any of the stellar coronae. This finding cannot be accidental and is thus longing for a physical explanation. If the low f/i ratios can reliably be interpreted as high densities, this would be strong evidence for non-coronal X-ray production mechanisms. We assessed the possibility of UV contamination, and under the assumption of blackbody radiation producing the UV emission measured at the wavelengths of consideration, the inferred radiation temperatures are far too low to be of any significance and allow avoiding conclusions of high densities. Unless a different conversion of measured UV fluxes into radiation temperatures is found this implies that the densities derived from He-like triplets are very secure.

In addition to the He-like triplets, the ratio of Fe XVII $\lambda\lambda$17.10/17.05 gives further evidence for a discrepancy between stellar coronae and cTTS. If we assume for the time being that this measurement is correct within the uncertainties given by Ness & Schmitt (2005) this again provides strong support for high densities, as in this case, UV contamination requires much hotter radiation fields than those required for the He-like lines (Mauche et al. 2001; 7).

The high densities are very much in support of an accretion shock scenario producing the X-ray emission. Unfortunately, we have no He-like f/i ratios from Mg XI and Si XIII, which are produced at much higher temperatures as O VII and Ne IX. In the case of an accretion shock, the temperatures required to produce these ions cannot be reached under reasonable conditions (the free-fall velocity is bounded by mass and radius of the star) and should therefore be of coronal origin with low densities. However, neither *Chandra* nor *XMM-Newton* measured sufficiently strong lines, as Mg and Si are underabundant, possibly due to grain formation (Stelzer & Schmitt 2004; 12). If, however, the Mg and Si emission is purely of coronal nature (with no underabundance of grain forming elements), one wonders about the weakness of these lines, and thus the weakness of the coronal contribution to the total emission. The same issue is also raised by the fact that no emission at all from the forbidden line of O VII is detected (see Fig. 1), implying that any coronal emission is not producing enough O VII flux to be measureable, neither with *Chandra* nor with *XMM-Newton*.

This is important to note, as other X-ray production mechanisms (e.g. shocks in jets, magnetic reconnection with the accretion disk) may also require high densities, possibly also at temperatures producing Mg XI and Si XIII. So far, detailed theoretical models have only been computed for the accretion shock scenario (Günther et al. submitted) and the proposed alternative scenarios have not been modelled in any detailed fashion to be confronted with observations. The present X-ray data have surely been explored very close to their limits and there is no doubt that the missions *Chandra* and *XMM-Newton* have provided essential and new information on the high energy emission from cTTS. In order to make further progress and address the remaining open issues, much deeper observations are necessary, with at least the same spectral resolution. From the viewpoint of TW Hya and cTTS in general the next-generation missions should therefore be a lot more sensitive in order to also observe less luminous cTTS, but the spectral resolution of *Chandra* is required to address the physics of the emission processes and should therefore not be sacrificed.

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