X-RAY EMISSION FROM CLASSICAL T TAURI STARS

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ABSTRACT

Young stars produce copious amounts of X-ray emission. The observed activity is usually interpreted as a scaled-up version of solar activity. High resolution spectroscopy on board XMM-Newton and *Chandra* of classical T Tauri stars (cTTS), i.e., stars being surrounded by presumably (still) accreting disks, shows spectral signatures very much different from the spectral signatures found in "normal", i.e., non-accreting, late-type stars. It is natural to attribute these spectral differences to accretion processes occurring in these objects and I will present and review the available evidence for accretion related X-ray emission in cTTS.

Key words: X-rays, stars, coronae, activity.

1. WHAT ARE T TAURI STARS AND WHY SHOULD ONE CARE ABOUT THEIR X-RAY EMISSION ?

T Tauri stars are pre main-sequence stars located in the HR-diagram between the zero age main-sequence and the so-called "Stellar Birth Line". Unlike evolved stars such stars have no condensed cores and show the typical signatures of youth and activity. One normally distinguishes between two classes of T Tauri stars, the so-called "classical T Tauri stars" (cTTS) and the "Weak Line" T Tauri stars (wTTS), based on the strength of the H_α line, which is always seen in emission in those stars. Because of its time variability, a classification scheme based on the H_α line alone is of limited practical use. In more physical terms, cTTS are thought to be class II objects, i.e. stars still surrounded by disks, while wTTS are class III objects, i.e. stars without any clear signatures of disks. Thus the important difference between class II and class III objects and hence between cTTS and wTTS is the presence of a disk which - of course - is thought to be accreting; there are cases of (debris) disks with very little or no accretion at all, which are not of interest in the present context.

Both classes of PMS stars, i.e. the cTTS and WTTS, are copious X-ray emitters Feigelson & Montmerle (1999). Low and medium resolution spectroscopy suggests the X-ray emission to be thermal with typical plasma temperatures of around 10 MK. Furthermore, the X-ray emission shows significant variability often in the form of powerful X-ray flares. Most PMS stars are very rapid rotators, at least when compared to the Sun. With this rapid rotation and their large outer convection zones PMS stars possess all the necessary ingredients to produce the "expected" and observed intense X-ray activity Feigelson & Montmerle (1999), which is usually attributed to a scaled-up version of solar activity. This interpretation is supported by the evidence for the presence of intense photospheric magnetic fields reaching a strength of a few kg (Valenti&Johns-Krull, 2004).

The same arguments should in principle also apply to cTTS. However, the presence of a disk allows for additional possibilities to produce high energy X-ray emission. Such possibilities include accretion, interactions between the star and the disk (if the disk is coupled to the star via the magnetic field), and jets among other suggested sources for high energy emission.

2. XMM-NEWTON HIGH RESOLUTION X-RAY SPECTROSCOPY OF CTTS

The proto-typical cTTS is the nearby TW Hya located at a distance of only 55 pc, thus being much closer than the cTTS in the Taurus Auriga, Chamaeleon or Lupus star forming regions. The key observation is the OVII triplet of TW Hya shown in Fig. 1, originally published by Stelzer & Schmitt (2004); a very similar result had been found by Kastner et al. (2002) based on observations with the *Chandra* HETGS. Surprisingly the forbidden line expected at 22.1 Å is extremely weak or absent in TW Hya. As a consequence the density of the X-ray emitting material in TW Hya must be extremely high and/or the radiation field, in which this material is immersed in, must be substantial and can in particular not be due to the photosphere of TW Hya, which is cool by comparison. It is important to keep in mind that the f/i-ratio observed in TW Hya is much smaller than the f/i ratios observed in all other cool stars (Ness et al., 2004) and therefore TW Hya differs in that respect from other cool stars. It is natural to ascribe this difference to a different X-ray emission process occurring in TW Hya.

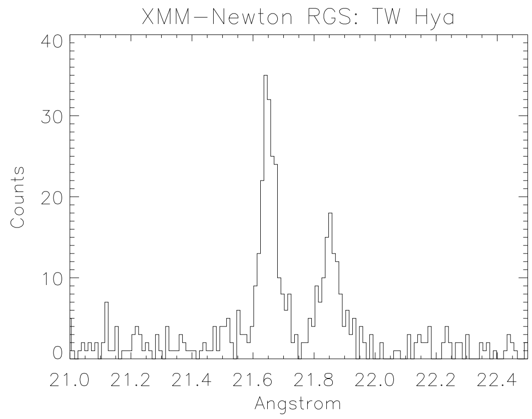

Figure 1. RGS-Newton O VII triplet in TW Hya around 21 Å; note the extreme weakness of the forbidden line at 22.1 Å.

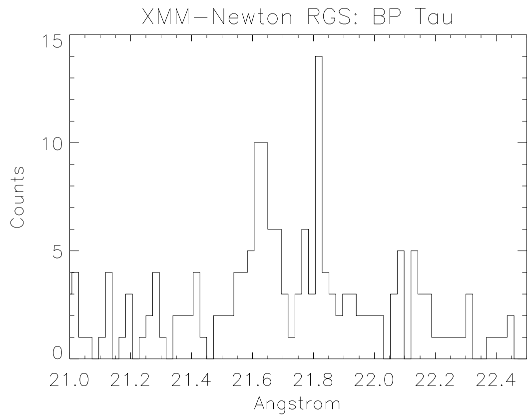

Figure 2. RGS-Newton O VII triplet in BP Tau around 21 Å; note again the extreme weakness of the forbidden line at 22.1 Å(cf. Fig. 1).

How typical a cTTS is TW Hya ? After all, its broad band X-ray spectrum significantly differs from that of other cTTS (Robrade & Schmitt, 2006). Further XMM-Newton spectroscopic observations were carried out on the cTTS BP Tau, whose cTTS nature is clearly demonstrated by the excess continuum (veiling) and Balmer emission (Bertout et al., 1988). There is debate about BP Tau's distance, and Wichmann et al. (1998) argue against BP Tau being an outlier from the Taurus-Auriga cloud as suggested by its HIPPARCOS parallax. From extensive optical monitoring Gullbring et al. (1996) conclude that optical variability is common in BP Tau, but in character very much different from variability encountered in typical flare stars. Most of the observed changes are slow and smooth and are interpreted as the result of inhomogeneous accretion from the disk onto the stellar surface. This view is strongly supported by the circular polarization in the He I λ 5876 emission line measured by Johns-Krull et al. (1999), who deduce a mean longitudinal magnetic field of 2460 ± 120 G in the line forming region and argue that accretion occurs preferentially along large-scale magnetic loops with a small filling factor. X-ray emission from BP Tau at a level of $\approx 10^{30}$ erg/sec was first reported by Walter & Kuhi (1981) using the *Einstein Observatory*.

The XMM-Newton RGS spectrum of BP Tau originally published by Schmitt et al. (2005)) is shown in Fig. 2; as is clear from Fig. 2, the signal-to-noise of this spectrum (SNR) is low but the small flux in the forbidden line is readily apparent and highly significant also in a somewhat noisy spectrum. The XMM-Newton RGS spectrum of BP Tau is very similar to that of TW Hya with respect to the anomalous oxygen and neon line ratios and the apparent absence of stronger iron lines especially near 15 Å and 17 Å despite the clear differences of their medium resolution broad band spectra (Robrade & Schmitt, 2006).

The cTTS CR Cha with spectral type K2 is located at a distance of 140–150 pc in the Chamaeleon star forming region with a measured RASS luminosity of 1.5×10^{30} erg/s (Feigelson et al., 1993); according to Meeus et al. (2003) it is a cTTS dominated by small amorphous silicates. In Fig. 3 we plot the XMM-Newton RGS spectrum of CR Cha (taken from Robrade & Schmitt (2006)); the SNR of this spectrum is clearly extremely low, but again the f/-ratio appears to be small albeit with significant error. A formal calculation of the OVII f/i ratio yields a value of $.61 \pm 0.51$. Therefore in summary, the OVII triplets of all cTTS studied with sufficient sensitivity to yield detections show f/i ratios below unity; this must be contrasted with the observational finding for normal stars, where the (by far) smallest f/i ratio is found for Algol (Ness et al., 2004), i.e., a binary system, where "pollution" through a nearby early-type star may in fact be responsible for the low O VII f/i-ratio..

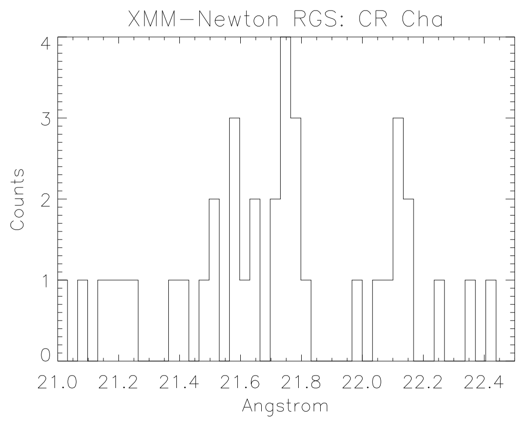

Figure 3. RGS-Newton O VII triplet in CR Cha around 21 Å; note again the extreme weakness of the forbidden line at 22.1 Å(cf. Fig. 1 and 2).

The same picture is found from an analysis of the Ne IX triplets in the spectral range between 13.4 - 13.7 Å. The analysis of the Ne IX triplet may be complicated because of the possible contamination with Fe XIX (see Ness et al.

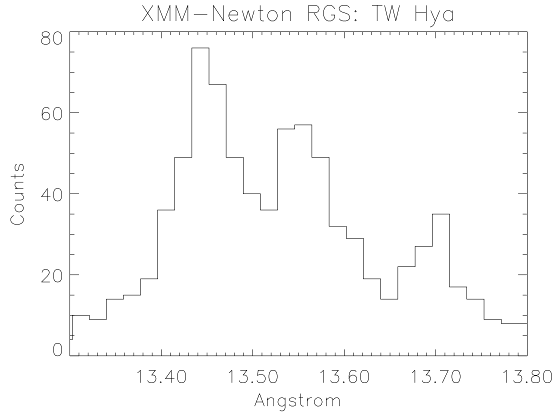

Figure 4. RGS-Newton Ne IX triplet in TW Hya around 13.5 Å; note again the extreme weakness of the forbidden line at 13.7 Å.

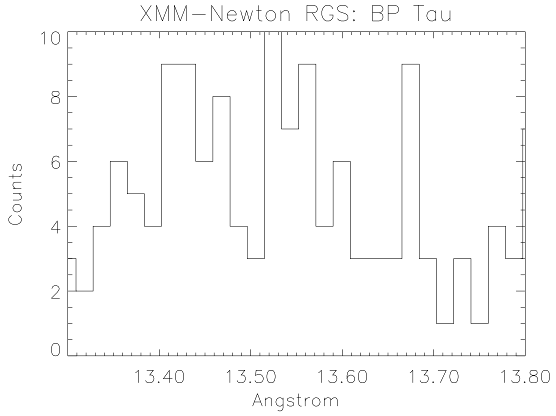

Figure 5. RGS-Newton Ne IX triplet in BP Tau around 13.5 Å; note again the extreme weakness of the forbidden line at 13.7 Å.

(2003)). While the contamination can be modeled, this modeling requires higher SNR data than usually available for cTTS. Fortunately, in the cases of TW Hya and BP Tau, the iron abundance appears to be low and iron lines are generally quite weak, so Fe XIX contamination is very likely not affecting the Ne IX f/i-ratio in a major way. In Fig. 4 and 5 I show the respective Ne IX triplets; in both cases the forbidden line is expected and seen at 13.7 Å, however, at a level considerably lower than the also present intercombination line at 13.55 Å. While in principle contamination of the 13.55 Å line cannot be excluded, this possibility seems unlikely, since both in TW Hya as well as BP Tau the FeXVII line at 15.03 Å, one of the strongest X-ray lines in other cool stars, is virtually absent.

3. MEDIUM RESOLUTION X-RAY SPECTROSCOPY OF CTTS

All of the cTTS were observed with XMM-Newton using somewhat different detector setups with exposure times in the range of 30-130 ksec. Data were taken with all X-ray detectors, which were operated simultaneously on board XMM-Newton, respectively the EPIC (European Photon Imaging Camera), consisting of the MOS and PN detectors and the RGS (Reflection Grating Spectrometer). The data for the cTTS SU Aur, where a high resolution RGS spectrum is available, is also included. However, since SU Aur is seen almost edge-on, absorption is very high and no clear detections of the O VII and Ne IX triplets were obtained. Also, for instrumental reasons, no PN data is available for this star. The detector modes were comparable, but different filters were used, the thick filter for the BP Tau and SU Aur and the medium filter for the CR Cha and TW Hya observations. However, the signal to noise ratio is differs substantially for the various targets and instruments. While the EPIC data quality is sufficient for all targets, for CR Cha only a rather small fraction of the original 100 ks data could be used for analysis because of very high background contamination; consequently the RGS spectrum of CR Cha is underexposed; a detailed account of these observations is given by (Robrade & Schmitt, 2006). The main point is that XMM-Newton provides simultaneous medium resolution spectroscopy for those periods of time where RGS high resolution spectroscopy is available. In Fig. 6 we show a comparative view of the medium resolution spectra of the four cTTS TW Hya, BP Tau, CR Cha and SU Aur.

While the EPIC spectra of BP Tau and CR Cha are obviously very similar, the spectrum of SU Aur indicates the presence of large amounts of extremely hot plasma noticeable, e.g. in the very strong Fe XXV line complex at 6.7 keV. On the other hand, the X-ray spectrum of TW Hya is very much softer, with very little emission present at higher energies. The observed spectra are also subject to absorption, affecting primarily the energy range below 1.0 keV. In these spectra the low energy slope mainly reflects the strength of the absorption, while the high energy slope traces temperature and amount of hot coronal and flaring plasma. Inspection of the two slopes indicates that the absorption is weakest for TW Hya, moderate for BP Tau and strongest for CR Cha and SU Aur, while the coronal component is strongest and hottest for SU Aur, followed by BP Tau and CR Cha and much weaker and cooler for TW Hya.

The EPIC data also allow the investigation of the X-ray light curves. A flare with a rise in count rate of factor 2.5–3 occurred during the BP Tau observation and a smaller flare (factor ~ 1.5) during the CR Cha observation. In the SU Aur data several flares were detected, the largest one showing an increase in X-ray brightness by a factor of 3, while TW Hya does not exhibit flaring during the XMM-Newton observations and any variability remains in the range of only 10%. However, light curve variations with factors around two are known for TW Hya (Kastner et al., 2002), who noted 'flares' during the observation ASCA and *Chandra* observations.

The light curves in connection with spectral hardness can be used to identify the origin of the variability. While in typical stellar coronal flares the emission measure of the

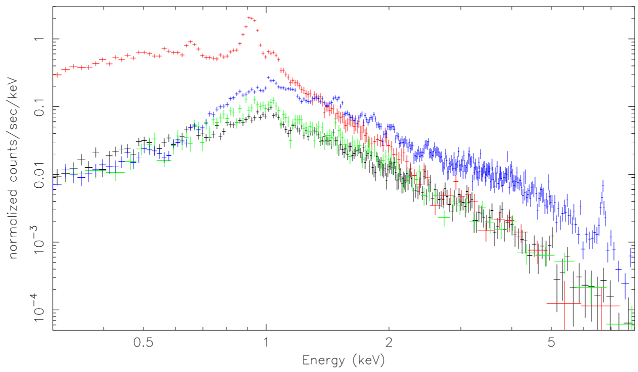

Figure 6. Medium resolution EPIC spectra of the cTTS BP Tau (black), CR Cha (green), SU Aur (blue) and TW Hya (red); bottom to top of the 1.0 keV peak.

hot plasma and hence the hardness of the spectra is increased, in a pure accretion spectrum no spectral changes should accompany the brightening, since the plasma temperature only depends on the infall velocity and not the accretion rate. If, in addition, a coronal contribution with a temperature higher than that produced by accretion is present, a slight spectral softening should be observed. A hardness ratio can be computed for each light curve time bin and in Fig. 7 the hardness ratio vs. count rate is shown for the four cTTS BP Tau, CR Cha, SU Aur and TW Hya. The hardness ratio is here defined as HR=H-S/H+S with the soft band covering the energy range 0.2–1.0 keV and the hard band 1.0–10.0 keV. Errors are small compared to the observed shifts in hardness ratio. A clear correlation of X-ray brightness with spectral hardness is present for BP Tau, CR Cha and SU Aur, a behavior typical of stellar flares, suggesting a non-accretion origin of the variability. No strong correlation is found for variations on TW Hya, which are, however, quite small. An anti-correlation appears to be present for the larger variations, as expected for brightness changes due to an increase in accretion rate. This is reflected in the slope of the linear regression curves. It is positive for BP Tau, CR Cha and SU Aur, but slightly negative for TW Hya, it would, however, be interesting to perform the same analysis on a data set exhibiting larger amplitude variability.

4. CONCLUSIONS

High resolution spectroscopy on board XMM-Newton and *Chandra* has brought about a major change in our understanding of the X-ray spectra of cTTS (and other stellar X-ray sources in general). While low and medium resolution spectra of cTTS and wTTS look very similar if not indistinguishable, high resolution spectroscopy reveals subtle but very clear differences in the X-ray spectra between these source classes. It can be no coincidence that the O VII f/i-ratios in all cTTS observed with sufficient SNR show values lower than observed in all other coronal sources, and therefore there must be a physical reason for this finding. The assumption of X-ray emission produced in an accretion shock as originally proposed by (Kastner et al., 2002) is the most natural one, yet on the other hand, accretion alone probably does not account for the whole story. The high-energy emission of cTTS is hard to explain with an accretion scenario since the available maximum energy is well constrained by the free fall velocity; X-ray emission, for example at 6.7 keV as observed for SU Aur, can in fact not be explained in the context of an accretion scenario. Also, the very frequent flaring as observed in the COUP observations (cf., Favata et al. (2005)) suggests a magnetic rather than a pure accretion scenario. On the other hand, an hypothesized coronal component in stars as TW Hya and BP Tau must have a rather odd spectral behavior. After all, in practically all active stars one observes a reasonably strong OVII forbidden line. If such a component also exists in cTTs, why is it then so weak ? Many questions remain open and further progress will surely come from more high resolution X-ray spectra of cTTS and theoretical modeling of accretion shocks.

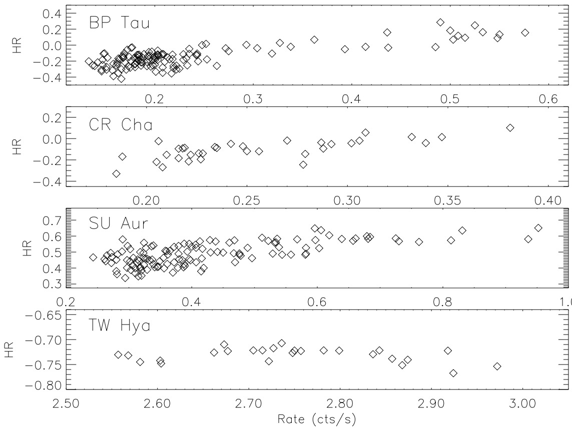

Figure 7. Hardness ratio vs. count rate of the sample cTTS, PN (SU Aur – MOS) data with 1 ksec binning.

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