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Letter to the Editor

The X-ray soft excess in classical T Tauri stars

M. Güdel[1,2] and A. Telleschi[1]

[1] Paul Scherrer Institut, Würenlingen and Villigen, 5232 Villigen PSI, Switzerland
e-mail: [guedel;atellesc]@astro.phys.ethz.ch
[2] Max-Planck-Institute for Astronomy, Königstuhl 17, 69117 Heidelberg, Germany

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ABSTRACT

Aims. We study an anomaly in the X-ray flux (or luminosity) ratio between the O VII $\lambda\lambda$21.6-22.1 triplet and the O VIII Lyα line seen in classical T Tauri stars (CTTS). This ratio is unusually high when compared with ratios for main-sequence and non-accreting T Tauri stars (Telleschi et al. 2007c, A&A, 468, 443). We compare these samples to identify the source of the excess. A sample of recently discovered X-ray stars with a soft component attributed to jet emission is also considered.
Methods. We discuss data obtained from the *XMM-Newton Extended Survey of the Taurus Molecular Cloud* (XEST) project, complemented by data from the published literature. We also present data from the CTTS RU Lup.
Results. All CTTS in the sample show an anomalous O VII/O VIII flux ratio when compared with WTTS or MS stars. The anomaly is due to an *excess* of cool, O VII emitting material rather than a deficiency of hotter plasma. The excess plasma must therefore have temperatures of $\lesssim$2 MK. This *soft excess* does not correlate with UV excesses of CTTS, but seems to be related to the stellar X-ray luminosity. The spectra of the jet-driving TTS do not fit into this context.
Conclusions. The soft excess depends both on the presence of accretion streams in CTTS and on magnetic activity. The gas may be shock-heated near the surface, although it may also be heated in the magnetospheric accretion funnels. The soft component of the jet-driving sources is unlikely to be due to the same process.

Key words. stars: coronae – stars: formation – stars: pre-main sequence – X-rays: stars

1. Introduction

Classical T Tauri stars (CTTS) are optically revealed young stars distinguished by spectra showing strong line emission of, for example, Hα or Ca II H&K. Their Hα and ultraviolet (UV) line and continuum emission is 10^2–10^4 times stronger than in active main-sequence (MS) stars, regardless of the photospheric effective temperature, but correlates with the mass accretion rates derived from the optical continuum (Bouvier 1990; Johns-Krull et al. 2000). The consensus, based on such correlations and line profiles, is that accreting material is heated in shocks near the stellar surface (e.g., Calvet & Gullbring 1998; Gullbring et al. 1998). Some of the emission lines (e.g., Hα, Ca II) may also form in the accretion funnels or in stellar winds (Ardila et al. 2002).

Nearly free-falling gas will indeed heat to maximum temperatures $T_s = 8.6 \times 10^5$ K $[M/(0.5\,M_\odot)][R/(2\,R_\odot)]^{-1}$ in shocks (Calvet & Gullbring 1998). UV and optical line emission thus diagnoses the accretion velocity, the mass accretion rate, and possibly the surface filling factor of accretion funnels. If the photoelectric absorption by the accreting gas is small, then the softest X-ray range may reveal the high-T tail of the shock emission measure. Güdel (2006), Telleschi et al. (2007c) and Güdel et al. (2007c) were the first to identify an excess in the O VII/O VIII Lyα flux (or luminosity) ratio in CTTS when compared with MS stars, or weak-line T Tauri stars (WTTS) in the *XEST* project (Güdel et al. 2007a), the so-called X-ray *soft excess* of CTTS. This feature may define the high-T continuation of the excess emission diagnosed for the 10^4–10^5 K range.

The appreciable accretion rates predict shock densities of $n_e \approx 10^{12}$–10^{14} cm^{-3}, as indeed first reported for the CTTS TW Hya from line diagnostics of O VII and Ne IX, forming at a few MK (Kastner et al. 2002; Stelzer & Schmitt 2004). However, some accreting young stars show much lower n_e, such as AB Aur (Telleschi et al. 2007b) and T Tau (Güdel et al. 2007c); the same discrepancy between expected and observed n_e has also been reported from UV density diagnostics (Johns-Krull et al. 2000).

Here, we present new evidence for the soft excess and discuss it in a larger context. We are interested in comparing CTTS with WTTS to assess whether the anomaly can be attributed to accretion in CTTS; we will therefore include WTTS as a test sample and compare with samples of MS stars. Further, we will test whether the anomalous O VII/O VIII flux ratio is due to a high O VII flux or rather due to a suppressed O VIII Lyα flux. We compare these stellar samples with a small group of accreting, jet-driving stars which also show an anomalous soft component (Güdel et al. 2007b). In addition, we compare the X-ray soft excess with UV line and continuum excesses reported earlier.

2. Data and results

Ratios between fluxes in the O VII triplet ($\lambda\lambda$21.6, 21.8, 22.1, summed over all three lines) and the O VIII Lyα λ18.97 line have been derived from fluxes from Telleschi et al. (2007c) (for the WTTS HD 283572, V773 Tau, V410 Tau, and HP Tau/G2; for the CTTS SU Aur, DH Tau, DN Tau, BP Tau; and for the Herbig star AB Aur), Güdel et al. (2007c) (for the CTTS T Tau N), Robrade & Schmitt (2006) (for the CTTS BP Tau, TW Hya, and CR Cha), Argiroffi et al. (2005) (for the multiple CTTS-WTTS system TWA 5; it is unknown whether the CTTS or the WTTS is the dominant X-ray source), Günther et al. (2006) (for the CTTS V4046 Sgr), and Argiroffi et al. (2007) (for the old CTTS MP Mus), and our own analysis for the CTTS RU Lup[1].

We determined the unabsorbed fluxes by correcting for wavelength-dependent transmission, as calculated in XSPEC using the "wabs" model. We used the absorption column densities, $N_{\rm H}$, toward the target stars, also given by the above authors. We adopted $N_{\rm H} = 10^{21}$ cm^{-3} for V4046 Sgr, as suggested by Günther et al. (2006). Finally, line luminosities were calculated using the published distances.

Total X-ray luminosities, $L_{\rm X}$, were taken from the same authors; for V4046 Sgr, the spectral line fluxes are about half as high as for TW Hya (see comparison in Günther et al. 2006) while the distance seems to be very uncertain; we adopted a distance of 83 pc (Quast et al. 2000); the uncertainties will not be crucial for our investigation. For MP Mus, distance and $L_{\rm X}$ are from Mamajek et al. (2002).

Data for solar-analog (G-type) MS stars were taken from Telleschi et al. (2005), and for a larger MS sample from Ness et al. (2004). These authors list $L_{\rm X}$, the energy fluxes (in erg cm^{-2} s^{-1}) in the O VIII Lyα line and in the O VII Heα triplet (only the r line in Ness et al. 2004), from which L(O VIII) resp. L(O VII) were calculated. For these stars, $N_{\rm H}$ is low and does not need to be considered.

Figure 1 highlights the soft excess for the CTTS T Tau N. The figure compares the X-ray spectrum of the active, evolved binary HR 1099 dominated by emission from a K-type subgiant (top panel; archival *XMM-Newton* data, see Audard et al. 2001) with the spectrum of the weakly absorbed WTTS V410 Tau (Telleschi et al. 2007c), the CTTS T Tau (Güdel et al. 2007c), and the old single F-type star Procyon (archival *XMM-Newton* data, see Raassen et al. 2002). HR 1099 and V410 Tau show the typical signatures of a hot, active corona: a strong continuum, strong lines of Ne X, and highly-ionized Fe lines but little flux in the O VII line triplet. In contrast, the spectrum of Procyon is dominated by lines of C, N, and O, the O VII triplet exceeding the O VIII Lyα line in flux. The observed spectrum of T Tau reveals a hybrid situation, with signatures of a very active corona shortward of 19 Å but also an unusually strong O VII triplet. Due to the fact that its hydrogen absorption is large (in contrast to V410 Tau – note the latter's N VII Lyα λ24.8 line formed over a wide temperature range), we have modeled the intrinsic, unabsorbed spectrum based on transmissions determined in XSPEC (based on the "wabs" model) using $N_{\rm H}$ from Güdel et al. (2007c) ($N_{\rm H} = 4.9 \times 10^{21}$ cm^{-2}), but also the somewhat lower value found from EPIC spectra ($N_{\rm H} \approx 3 \times 10^{21}$ cm^{-2}; Güdel et al. 2007a). In either case, the O VII lines are now the strongest in the X-ray spectrum, reminiscent of the situation in Procyon.

Figure 2 shows the measured (absorbed) O VII/O VIII Lyα photon-flux ratio, S, versus the X-ray determined $N_{\rm H}$ [2]. CTTS and WTTS are marked, respectively, by filled (red) and open (blue) circles; the flaring CTTS SU Aur and DH Tau are marked by small, filled circles. The dotted lines mark the loci of S for an

[1] *XMM-Newton* ObsID 0303900301, observed on 2005 August 8 during 29.8 ks; data reduction followed the same procedures as described by Güdel et al. (2007a) and Telleschi et al. (2007c); the line fluxes were found from spectral fits based on the apec model in the XSPEC software package (Arnaud 1996). Key results: Three spectral components with $kT_1 = 0.24$ keV, $kT_2 = 0.92$ keV, and $kT_3 = 3.6$ keV; emission measure ratio = 1.0:2.9:1.5; $N_{\rm H} = 1.6 \times 10^{21}$ cm^{-2}. Luminosity of the O VII triplet: $(4.0\pm1.4) \times 10^{28}$ erg s^{-1}; of the O VIII Lyα line: $(4.1\pm1.4) \times 10^{28}$ erg s^{-1}; total X-ray [0.3 keV, 10 keV] luminosity: $L_{\rm X} = 1.9 \times 10^{30}$ erg s^{-1}. The distance to RU Lup is 140 pc (Bertout et al. 1999).

[2] DN Tau has been reconsidered, with very similar results as in Telleschi et al. (2007c); for SU Aur and HP Tau G2/G3, upper limits to the O VII flux derived by Telleschi et al. (2007c) (see also their Fig. 8) have been adopted; BP Tau is plotted twice, given the discrepant $N_{\rm H}$ values between Robrade & Schmitt (2006) and Telleschi et al. (2007c).

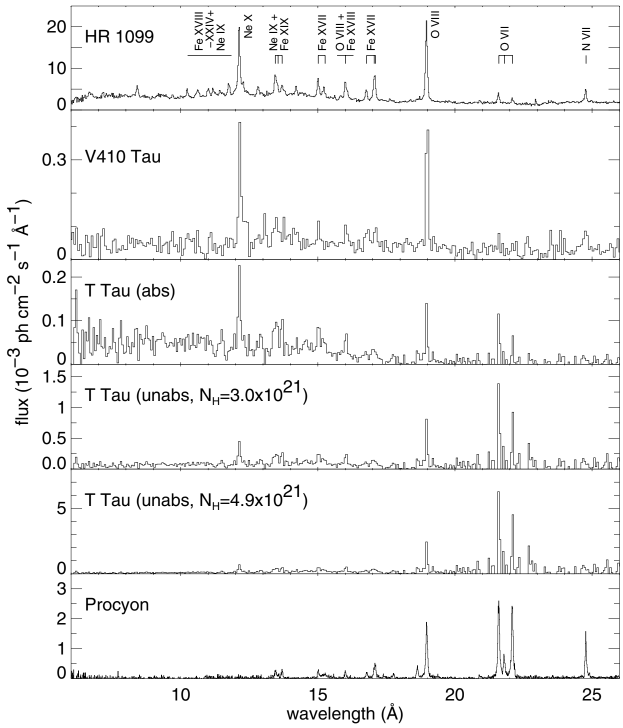

Fig. 1. Comparison of fluxed X-ray photon spectra of (*from top to bottom*, all from *XMM-Newton RGS*) the active binary HR 1099, the WTTS V410 Tau, the CTTS T Tau, the T Tau spectrum modeled after removal of absorption (two versions, using $N_{\rm H} = 3 \times 10^{21}$ cm^{-2} and 4.9×10^{21} cm^{-2}, respectively), and the inactive MS star Procyon. The bins are equidistant in wavelength (*from top to bottom*, the bin widths are, respectively, 0.025 Å, 0.070 Å, 0.058 Å, 0.058 Å, 0.058 Å, and 0.010 Å).

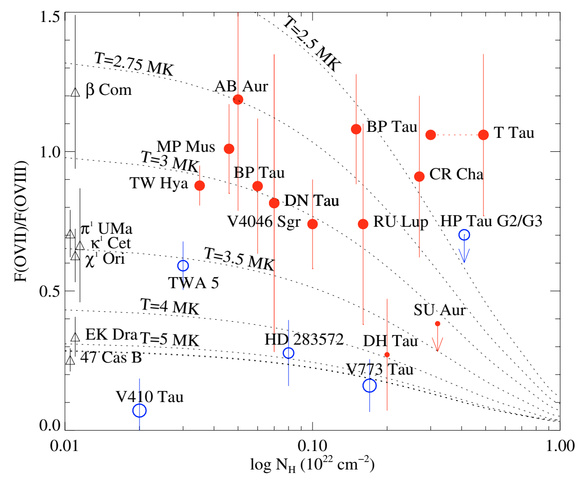

Fig. 2. The ratio between O VII and O VIII Lyα photon fluxes (each in units of ph cm^{-2} s^{-1}, absorbed) for CTTS (red, filled circles) and WTTS (blue, open circles) versus $N_{\rm H}$. Two flaring CTTS are shown by small, filled circles. The loci of MS solar analogs are shown by black triangles near $N_{\rm H} \approx 0.01$ although their true $N_{\rm H}$ are much lower. The dotted lines give the ratios for isothermal plasmas with temperatures as labeled. BP Tau is plotted twice, once after Robrade & Schmitt (2006) (larger $N_{\rm H}$) and once after Telleschi et al. (2007c). The high- and low-absorption solutions for T Tau are connected by a dotted line.

isothermal plasma; the labels give the electron temperatures. The plasma contributing to O VII and O VIII is, however, not isothermal as the hotter plasma also contributes to the O VIII flux. All CTTS show $S \approx 1 \pm 0.25$ in this range of N_H. WTTS are found at much lower values; their published spectra show at best marginal evidence of the O VII triplet (e.g., Telleschi et al. 2007c).

MS solar analogs are plotted near $N_H = 0.01$ although their true N_H are much lower. Characteristic coronal temperatures, T, of MS stars are a function of L_X. For solar analogs at different activity levels, T increases from $\approx$2 MK for a solar twin with $L_X \approx 10^{27}$ erg s^{-1} to $T \approx 10$ MK for a ZAMS star with $L_X = (1{-}3) \times 10^{30}$ erg s^{-1} (Telleschi et al. 2005). Consequently, S is expected to decrease toward higher activity levels (i.e., the O VII line becomes progressively less important; Fig. 1). This is indeed the case, the most active solar analog in the sample, 47 Cas B, showing $S \approx 0.26$, and the least active one, β Com, $S \approx 1.21$. The values of S for WTTS and the two active, near-ZAMS stars 47 Cas B and EK Dra are similar, whereas for CTTS they are similar to inactive solar analogs with ages of $\approx$1 Gyr.

Figure 3a shows the ratio between the intrinsic (unabsorbed) luminosities of the O VII r and the O VIII Lyα lines as a function of L_X, comparing with solar analogs from Telleschi et al. (2005) and the larger MS sample from Ness et al. (2004). For the TTS of Telleschi et al. (2007c), a good approximation to compute L(O VII r) from L(O VII) is L(O VII r) = 0.55L(O VII) (Porquet et al. 2001)[3]. The trend of a decreasing ratio with increasing L_X for MS stars is followed by the sample of WTTS, while CTTS again show a significant excess. This also holds if the surface X-ray flux ($L_X/[4\pi R_*^2]$) is used on the abscissa (not shown).

In principle, a suppressed O VIII Lyα flux in CTTS would produce the same anomaly, but as we show in Fig. 3b, L(O VIII) of CTTS and WTTS both follow the same trend (rather than being suppressed for CTTS by a factor of $\approx$3–4), also indistinguishable from MS stars. Therefore, the CTTS *soft excess* is due to an excess in the O VII flux.

We also consider a sample of strongly accreting *Two-Absorber X-ray* (TAX) sources which show an anomalous soft component additional to a much more strongly absorbed coronal component; the soft component contributes essentially all of the observed O VII and O VIII Lyα flux; it has been interpreted as originating from the base of jets (Güdel et al. 2007b). The low-resolution EPIC spectra are not useful to derive an S ratio, but the spectral fits are appropriate to estimate the luminosity in the dominant O VIII Lyα line from the model. Overplotting L(O VIII) in Fig. 3b shows a poor correlation, as should be expected because the coronal component shows a separate (harder) spectrum whose O VIII Lyα line is, however, entirely absorbed.

3. Discussion and conclusions

All CTTS (except the two flaring ones) show an *X-ray soft excess* defined by an anomalously high ratio between the fluxes of the O VII triplet and the O VIII Lyα line, compared to WTTS and MS stars. The anomaly refers to CTTS only, while WTTS show line ratios comparable with very active MS stars. In contrast, the correlation between L(O VIII) and L_X is indistinguishable between CTTS, WTTS, and MS stars, suggesting that the CTTS soft excess is indeed due to an excess of cool material with $T \lesssim 2$ MK rather than a relative suppression of the O VIII Lyα line (e.g., due to resonance scattering). The strongly

[3] We cannot strictly use the S ratio to derive the fractional flux of the O VII r line (Porquet et al. 2001) because the plasma is unlikely to be isothermal.

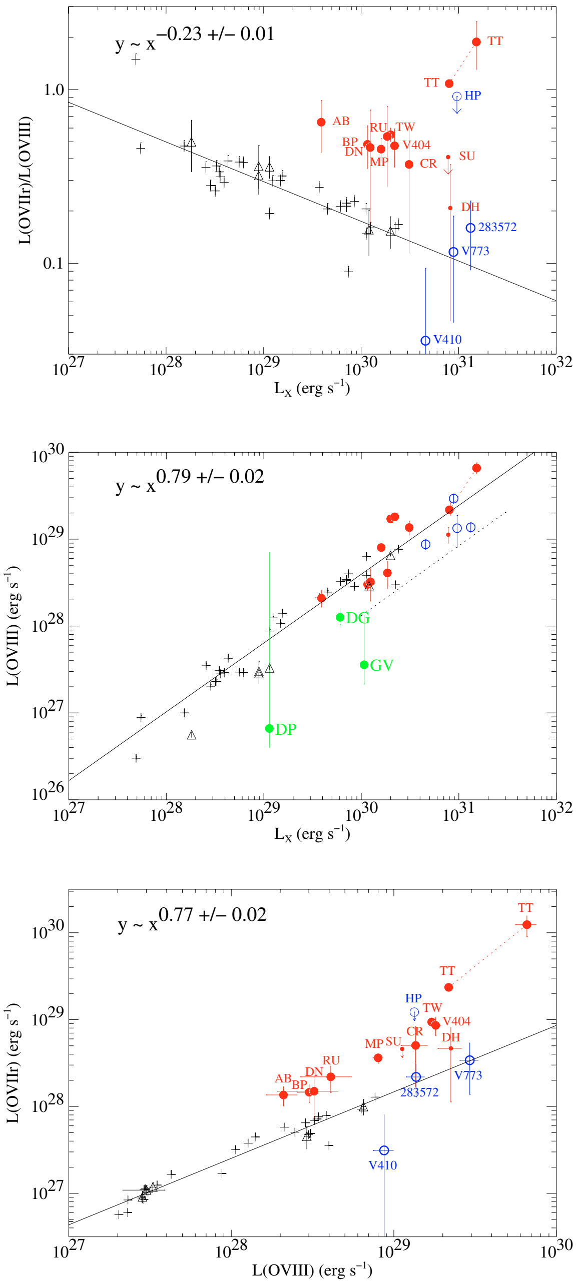

Fig. 3. *Top* **(a)**: the ratio between O VII r and O VIII Lyα luminosities (each in units of erg s^{-1}) vs. L_X. Labels give initial letters of stellar names. Crosses mark MS stars (from Ness et al. 2004), triangles solar analogs (from Telleschi et al. 2005), filled (red) circles CTTS, and open (blue) circles WTTS. The high- and low-absorption solutions for T Tau are connected by a dotted line. The solid line is a power-law fit to the MS stars with $L_X > 10^{27}$ erg s^{-1} (the relation between the variables is given in the upper left corner). *Middle* **(b)**: correlation between L(O VIII) and L_X for MS stars. Symbols are as in Fig. 3a. All three samples follow the same trend (solid line for MS stars). The dotted line corresponds to a suppression of L(O VIII) by a factor of 3. Also shown are three TAX sources (filled, green, labeled: DG Tau, GV Tau, DP Tau). *Bottom* **(c)**: correlation between L(O VII r) and L(O VIII). Symbols are as in Fig. 3a.

accreting TAX sources do not fit into this picture; strong absorption makes their *coronal* O VII and O VIII Lyα lines inaccessible.

Is the X-ray *soft excess* described here the high-temperature equivalent of the UV/optical continuum and line excesses? We correlated L(O VII r), which is dominated by the excess emission, with UV Si II, Si IV, C IV, and λ1958 continuum luminosities (all strongly dominated by excess emission) derived from fluxes presented by Valenti et al. (2000), applying the $R = 3.1$ extinction law given by Cardelli et al. (1989). No correlation was found. This is not very surprising given that the UV excess luminosities amount to 10^2-10^4 times the levels of "normal" stars, with a large scatter over the entire range (Johns-Krull et al. 2000), while the O VII excess is comparatively small. Figure 3 in fact suggests that for most CTTS reported here, the L(O VII r)/L(O VIII) ratio is a factor of ≈3–4 that of equivalent MS stars, i.e., L(O VII r) scales with L(O VIII) as in MS stars, except that it is enhanced by a factor of ≈3–4. L(O VIII) in turn is "normal" and scales with L_X (Fig. 3b). Because O VII and O VIII have overlapping formation temperature ranges, their flux ratio cannot take arbitrary values for reasonable EM distributions. However, much larger (but also smaller) excesses are easily possible given the variations in the UV excess. For very cool excess plasma, the added O VII flux could be small and the correlation with the UV excess be masked by scatter, but then the O VII would be close to the "normal" coronal level.

The L(O VII r) vs. L(O VIII) relation is shown in Fig. 3c (to avoid larger error bars, we have used L(O VII r) without the minor correction for the non-excess contribution). This trend does not connect with the behavior of the UV excess at *lower* T but is reminiscent of the systematic factor ≈2 deficiency of (harder) X-rays from *hotter* plasma in CTTS with respect to WTTS (Telleschi et al. 2007a). It appears that the *X-ray soft excess depends on the level of magnetic ("coronal") activity.* At the same time, *it depends on the presence of accretion*.

Magnetic accretion streams may shock-heat gas at the impact point in the stellar photosphere to X-ray emitting temperatures. If L(O VII r) $\propto \dot{M}$ (similar to the UV excess, Johns-Krull et al. 2000), and since $\dot{M} \propto M^2$ (Muzerolle et al. 2003), $L_X \propto M^{1.7\pm0.2}$ (Telleschi et al. 2007a), and L(O VIII) $\propto L_X^{0.79\pm0.02}$ (Fig. 3b), one might expect L(O VII r) $\propto L$(O VIII)$^{1.49\pm0.18}$ although this is not a physical relationship. This relation is steeper than in Fig. 3c; also, a direct correlation with the UV excess (which itself correlates with $\dot{M}$; Johns-Krull et al. 2000) is not seen.

On the other hand, the two dependencies may point to an interaction between accretion and magnetic activity. The cool, infalling material may partly cool pre-existing heated coronal plasma, or reduce the efficiency of coronal heating in the regions of infall (Preibisch et al. 2005; Telleschi et al. 2007c; Güdel et al. 2007c). A model of this kind in which the soft excess is formed *in the accretion funnels* by the coronal heating process would make a correlation with the (coronal) L_X plausible, and would at the same time explain why CTTS are statistically X-ray fainter compared with WTTS (Preibisch et al. 2005; Telleschi et al. 2007a). The deficit of hot material may then reflect in additional, cooled (or less heated) plasma evident in the soft excess in CTTS, i.e., the soft excess connects to the hotter, coronal EM, as observed, rather than to the cooler UV excess. Either way, it clearly argues in favor of a substantial influence of accretion on the X-ray properties of pre-main sequence stars.

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