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Anomalous X-ray line ratios in the cTTS TW Hydrae

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ABSTRACT

The cTTS TW Hya has been observed with high-resolution X-ray spectrometers. Previously found high densities inferred from He-like f/i triplets strongly suggested the detected X-ray emission to be dominated by an accretion shock. Because of their radiation field dependence He-like f/i ratios do not provide unambiguous density diagnostics. Here we present additional evidence for high densities from ratios of Fe XVII lines. Key Fe XVII line ratios in TW Hya deviate from theoretical expectations at low densities as well as from the same measurements in a large sample of stellar coronae. However, a quantitative assessment of densities is difficult because of atomic physics uncertainties. In addition, estimates of low optical depth in line ratios sensitive to resonance scattering effects also support a high-density emission scenario in the X-ray emitting regions of cTTS.

Key words. X-rays: stars – stars: individual: TW Hya – stars: pre-main sequence – stars: coronae – stars: activity – accretion

1. Introduction

T Tauri stars are young pre-main sequence (PMS) late-type stars. "Classical" T Tauri stars (cTTS) are thought to still be surrounded by accretion disks as evidenced by IR and UV excess, while no signs for the presence of a disk are found in the so-called "weak line" T Tauri stars (for details we refer to Feigelson & Montmerle 1999). X-ray emission from PMS stars is expected to be high because of their fast rotation if the emission is interpreted as scaled-up solar-type activity. However, for cTTS an additional source of X-ray emission through accretion is available; this additional X-ray production mechanism is expected to lead to significant differences in X-ray emission levels and variability, but in particular to differences in the spectral properties of the X-ray emission.

High-resolution X-ray observations with the transmission and reflection gratings aboard *Chandra* and *XMM-Newton* have now been obtained for about two dozens of stars, but only for very few cTTS. The best data are usually obtained for the O VII triplet located at 21.6 Å ("r-line"), 21.8 Å ("i-line"), and 22.1 Å ("f-line"). The f/i-line ratio is density-sensitive (Gabriel & Jordan 1969), but in all cases no ratios below unity are encountered for coronal sources (Ness et al. 2004). In contrast, the available high-resolution spectra of cTTS show unusually low He-like f/i ratios in TW Hya (Kastner et al. 2002; Stelzer & Schmitt 2004) and BP Tau (Schmitt et al. 2005). The first obvious conclusion was that the plasma in cTTS is at extremely high densities suggesting its origin in an accretion shock rather than a "normal" magnetically active corona (Kastner et al. 2002). However, f/i ratios could only be measured for O VII and Ne IX, and the f/i ratios of those ions also depend on UV radiation fields if they are strong enough and located close to the origin of the X-ray emission. Since the presumed accretion shock region is also expected to produce intense UV emission, the observed low f/i-ratios would then not contradict the accretion hypothesis, but need not necessarily imply high densities.

The *Chandra* HETGS spectrum of TW Hya has already been analyzed by Kastner et al. (2002) with a variable abundance differential emission measure analysis and the identification and discussion of the anomalously low f/i-ratios in O VII and Ne IX. We address an alternative approach to density determination using Fe XVII lines at 17.05 Å and 17.10 Å. Mauche et al. (2001) were the first to use this ratio as density tracer in their study of the *Chandra* HETGS spectrum of the intermediate polar EX Hya, demonstrating that this ratio is considerably less sensitive to photoexcitation than He-like ions. Further, we investigate the effects of resonant line scattering which also depends sensitively on plasma density.

The atomic physics of Fe XVII, especially the 3d $\rightarrow$ 2p (15 Å range) and 3s $\rightarrow$ 2p (17 Å range) transitions, is quite complicated and extensive efforts have been spent with the conclusion that a number of indirect processes have to be considered apart from the standard collisional excitation (CE) theory. The inclusion of resonance excitation and inner-shell excitation from Fe XVI as well as radiative and dielectronic recombination from Fe XVIII improved the situation enormously, but residual discrepancies remain (for more details see Gu 2003). In view

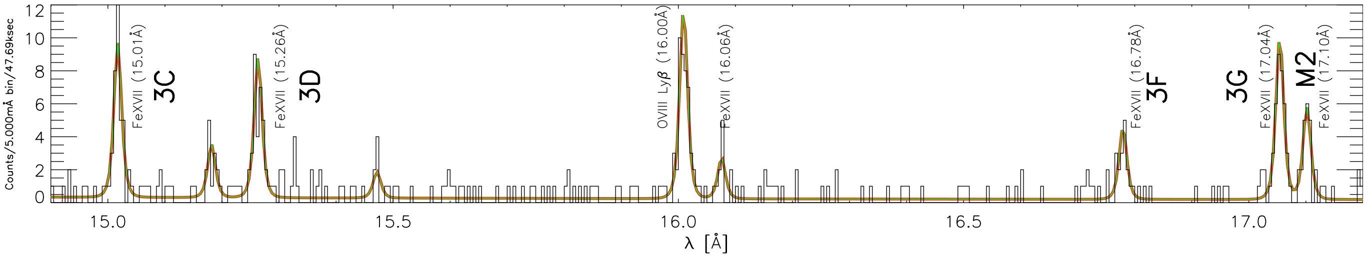

Fig. 1. HETGS spectrum and a parameterized best-fit model of TW Hya (summed plus- and minus orders); line letter designations refer to the line parameters given in Table 1.

of these difficulties we focus our analyses on the comparison of TW Hya with a sample of stellar coronae, but refrain from any quantitative determination of densities. Comparison with theoretical calculations is based on atomic data using APEC (Smith et al. 2001)[1] and the most recent calculations by Gu (2003).

2. Data reduction and analysis

Chandra observations of TW Hya (K7 Ve, $d = 57$ pc) were carried out with the High Energy Transmission Grating Spectrometer (HETGS; ObsID 5, 48 ks, June 2000); details are given by Kastner et al. (2002). We extracted count spectra using the Chandra Interactive Analysis of Observations (CIAO) software, but used our own tool CORA (Ness & Wichmann 2002) to determine line counts by fitting line templates and converted them to line fluxes using effective areas extracted with CIAO (using the tool `fullgarf`). After examining the spectra of the plus and minus sides we use the sum (representing the effective area-weighted average) for our analysis, which can be done if no anomalies occur on either side (which is not the case to our knowledge). Any correction of line fluxes for absorption is based on a value of $N_{\rm H} = 4 \times 10^{20}$ cm^{-2}, derived from a broad-band spectrum of TW Hya by Robrade et al. (2005). For comparison we extrated the HETGS spectra of various stellar coronae in exactly the same way to assess spectral differences between TW Hya and purely coronal sources.

3. Results

For our analyses we measured fluxes for two sets of lines, five lines of Fe XVII and the Lyα and Lyβ lines of H-like oxygen and neon. Figure 1 shows the HETGS spectrum between 15–17.2 Å illustrating the reliability of our line detections and flux measurements. The best fit above a source continuum of 20 cts/Å is also shown (*FWHM* 0.016 Å for all lines), and the derived counts and fluxes are listed in Table 1 together with the effective area values used for conversion of line counts to fluxes and the transmission efficiencies for $N_{\rm H} = 4 \times 10^{20}$ cm^{-2} calculated from Balucinska-Church & McCammon (1992); we assume standard cosmic abundances from Anders & Grevesse (1989). The Fe XVII line fluxes are corrected for absorption, but we did not correct the Lyα and Lyβ lines which will be investigated in detail below. In Table 1 we also list an Fe XVIII line at 16.07 Å (2p^{4}3s ^{2}P$_{5/2}$ to ground state) which we use to correct the O VIII Lyβ line at 16.00 Å to account for contamination by Fe XVIII at 16.004 Å (2p^{4}3s ^{2}P$_{3/2}$ to ground). The ratio of these two Fe XVIII lines varies slowly with temperature from 0.73 to 1.06 for $\log T = 6.3$–7.3 (as predicted by APEC). Given the low temperature of TW Hya, the measured flux in O VIII Lyβ was reduced by 75% of the flux in the 16.07-Å line. We corrected the stellar O VIII Lyβ line fluxes by interpolating the slow temperature dependence using temperature estimates from the ratio of lines of O VIII at 18.97 Å and O VII at 21.6 Å. The line fluxes in Table 1 are used to calculate the line flux ratios given in Table 2. For the Fe XVII line ratios the $N_{\rm H}$-corrected fluxes were used while the Lyβ/Lyα ratios are (not yet) corrected; the O VIII ratio is corrected for contamination with Fe XVII, but blending in the Ne X Lyα line is ignored.

Table 1. Line flux measurements for TW Hya.

λ [Å]	Counts	$A_{\rm eff}^{[\rm cm^2]}$	Ion	Transm.[a]	Flux[b]
3C 15.01	35.5 ± 6.2	16.0	Fe XVII	0.859	7.15 ± 1.26
3D 15.26	32.3 ± 6.0	23.2	Fe XVII	0.853	4.45 ± 0.83
[c]16.00	blend in O VIII		Fe XVIII	0.835	[1.15 ± 0.41][c]
[c]16.07	9.39 ± 3.4	19.0	Fe XVIII	0.834	1.53 ± 0.55
3F 16.78	16.6 ± 4.4	16.1	Fe XVII	0.816	3.13 ± 0.83
3G 17.05	37.6 ± 6.4	14.8	Fe XVII	0.809	7.64 ± 1.30
M2 17.10	21.2 ± 4.8	14.6	Fe XVII	0.807	4.36 ± 1.00
10.23	45.0 ± 7.3	83.7	Ne X	–	2.18 ± 0.35
12.13	200 ± 14.5	43.1	Ne X	–	15.8 ± 1.15
16.00	47.3 ± 7.1	19.2	O VIII	–	6.39 ± 0.97
18.97	121 ± 11.2	8.87	O VIII	–	29.8 ± 2.78

[a] Transmission efficiencies with $N_{\rm H} = 4 \times 10^{20}$ cm^{-2}.
[b] 10^{-14} erg cm^{-2} s^{-1}; corrected for $N_{\rm H}$.
[c] ~75% of 16.07-Å line blends with O VIII at 16.00 Å.

Table 2. Line flux ratios in TW Hya (notation as in Fig. 1).

$\lambda\lambda$	Flux ratio	av[a]	$\lambda\lambda$	Flux ratio	av[a]
M2/3G	0.57 ± 0.16	0.9	3D/3F	1.42 ± 0.46	0.6
3G/3F	2.43 ± 0.76	1.3	3G/3C	1.06 ± 0.26	0.8
M2/3F	1.39 ± 0.48	1.2	3G/3D	1.71 ± 0.43	2.1
3D/3C	0.62 ± 0.16	0.4	3F/3C	0.43 ± 0.19	0.6
O(β/α)	0.18 ± 0.03	0.14	Ne(β/α)	0.13 ± 0.02	0.14

[a] Error-weighted average of stellar measurements.

[1] Version 1.3.1; available at `http://cxc.harvard.edu/atomdb`

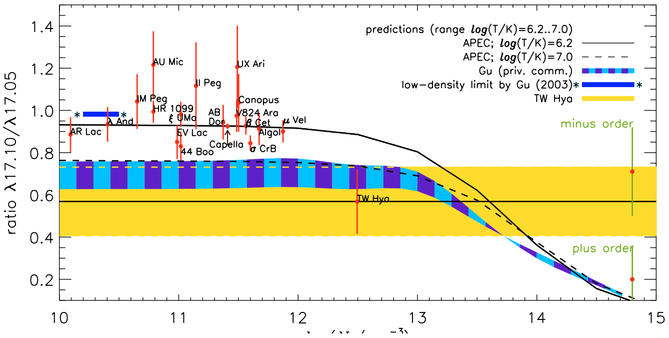

Fig. 2. Density dependence of the Fe XVII line ratio $\lambda\lambda 17.10/17.05$ predicted by APEC and M.F. Gu compared with 18 coronal measurements and TW Hya; plasma densities are derived from Ne IX f/i ratios.

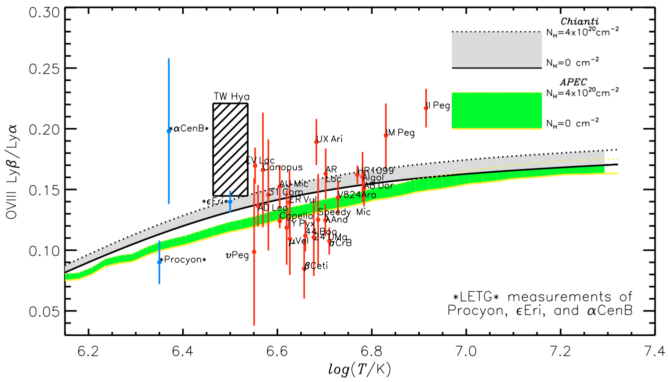

Fig. 3. Theoretical predictions of Lyβ/Lyα ratio as a function of temperature for O VIII and measurements of TW Hya compared with stellar measurements (temperatures from O VIII/O VII line ratios); shaded areas are predictions for values of $N_{\rm H} < 4 \times 10^{20}$ cm^{-2}.

We compare the line ratios of TW Hya with a large sample of analogous measurements of stellar coronae in a variety of classes. We first focus on the ratio $\lambda\lambda 17.10/17.05$ as a function of density in Fig. 2; TW Hya is indicated by the light shaded area denoting the 1σ uncertainty range from measurement errors. Stellar coronal densities are calculated from Ne IX f/i ratios given for 18 stars by Ness et al. (2004), cleared of all the Fe XIX blending. A clear discrepancy between all stellar measurements and TW Hya can be recognized. Theoretical predictions from APEC and Gu (priv. comm.; not yet including indirect processes), all in the temperature range $\log T = 6.2$–7.0, are shown for two temperatures bracketing those temperatures where the bulk of the Fe XVII line formation is expected to occur. While with APEC a quantitative determination of a high density $\sim 4 \times 10^{13}$ cm^{-3} is possible, the measurement of TW Hya does not deviate from the low-density limit as predicted by Gu. The stellar measurements appear more consistent with the APEC-prediction, however, since all coronal sources are thought to be far hotter than $\log(T/{\rm K}) = 6.0$, also APEC underpredicts the measured 17.10/17.05-ratios. In contrast, the calculations by Gu (2003), including indirect processes (but providing only the low-density limit at different temperatures), agree very well with the stellar measurements and an expansion of these calculations including all indirect processes as a function of density is likely to provide better estimates for TW Hya. Obviously, the observed Fe XVII 17.10/17.05-ratio in TW Hya is smaller than that typically measured in coronal sources and it is larger than in EX Hya (cf. Mauche et al. 2001), suggesting a plasma density in TW Hya larger than typically encountered in coronal sources, but smaller than 2×10^{14} cm^{-3} as inferred for EX Hya. We also compare more ratios in Table 2 with our stellar sample. In particular we found TW Hya to be different in the ratios $\lambda\lambda 17.05/16.78$ (3G/3F) and $\lambda\lambda 15.26/15.01$ (3D/3C), while in the other ratios no differences between TW Hya and the stellar sample are found. This suggests that the 17.05-Å and the 15.26-Å lines are anomalously enhanced in TW Hya while those at 15.01 Å, 16.78 Å, and 17.10 Å show no peculiarities.

A comparative analysis of the line ratios $\lambda\lambda 15.26/15.01$ and (3D/3C) $\lambda\lambda 15.26/16.78$ (3D/3F) has been carried out by Ness et al. (2003) to investigate opacity effects. For both ratios TW Hya shows significantly larger ratios possibly indicating resonant line scattering effects. However, laboratory experiments suggest blending of the 15.26-Å line with an Fe XVI satellite line (e.g., Brown et al. 2001), possibly explaining a trend of increasing $\lambda\lambda 15.26/15.01$-ratios with decreasing temperature (Ness et al. 2003). Since TW Hya does have relatively low X-ray temperature (Kastner et al. 2002; Stelzer & Schmitt 2004), the same reason can account for the anomalously high flux in the 15.26-Å line. In view of this ambiguity we also studied the H-like Lyβ/Lyα line ratios of O VIII and Ne X. In Fig. 3 we show a sample of stellar ratios of O VIII with the blending correction applied as described above, compared with the measurement of TW Hya and atomic data predictions; the same line ratio has been used by Testa et al. (2004) finding II Peg and IM Peg to be anomalous. The TW Hya measurement is marked with the hashed box bracketing the formal 1σ uncertainties in the line ratio and in temperature. Theoretical predictions from APEC and *Chianti* agree quite well with each other and uncertainties in $N_{\rm H}$ do not lead to different conclusions. However, we note in this context that the above blending correction is not straightforward, since it is predicted rather differently by *Chianti* and APEC (which we used for the correction). In view of the stellar measurements and the fact that the error bars do not include uncertainties from the blending correction, this deviation from theory appears rather marginal. We carried out the same procedure for the Ne X lines and found no deviation from the stellar measurements (Table 2).

4. Discussion and conclusions

We identified and measured a new line flux ratio sensitive to density, which strongly supports earlier conclusions of high plasma densities in TW Hya. The ratio of $\lambda\lambda 17.10/17.05$ is a sensitive tracer of high densities with little contamination from UV radiation or temperature. Besides the extremely low f/i ratios in O VII and Ne IX we also found this ratio to be anomalously low compared to all stellar coronae. Unfortunately, quantitative constraints on density are still ambiguous because theoretical calculations do not yet cover the full range of interactions between the ground state and excited states. At any rate, the density of TW Hya appears to be higher than that of typical stellar coronae, but lower than that of the intermediate

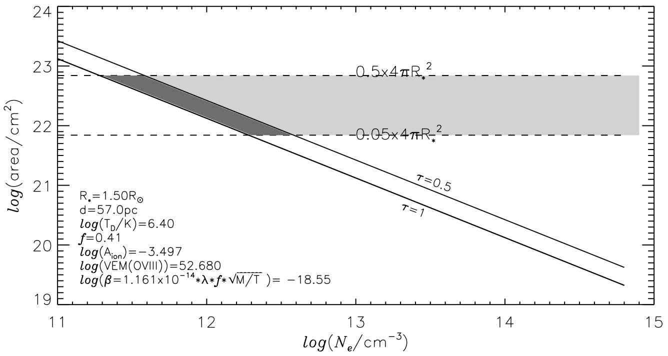

Fig. 4. Area vs. density N_e from the requirement optical depth $\tau < 1$; area values for surface filling factors are indicated.

polar EX Hya. Unambiguous X-ray density measurements as obtained here are also important for other cTTS.

The 15.01-Å and 15.26-Å Fe XVII lines provide a sensitive test for the effects of resonant line scattering. A comparison of this ratio for TW Hya with a sample of cool stars (Ness et al. 2003) shows a large value for TW Hya albeit with substantial error; similarly large values are found for EV Lac and Prox Cen. However, as discussed by Ness et al. (2003) the relative strength of the 15.26-Å line can also be explained by blending with low-temperature lines, leading us to conclude that the line ratio of the 15.01-Å and 15.26-Å lines provides no unambiguous evidence for resonance scattering in TW Hya. Next, we examined the ratios of H-like Lyβ/Lyα lines, which are also sensitive to resonant scattering (cf. Fig. 3). While the Lyβ/Lyα line ratio for TW Hya is clearly above the theoretical expectation, it does not differ significantly from those encountered in stellar coronae. Also, there is a nagging uncertainty about the blending correction with Fe XVIII, so that any resonant scattering effects appear marginal. Since the situation is similar for Ne X we conclude that there is no clear evidence for any X-ray optical depth effects in TW Hya and that the optical depth τ should be below unity.

The apparent absence of resonant scattering and the value of the observed emission measure in a line can be combined as follows: we use the formula for the optical depth τ at line center derived by Bhatia & Saba (2001) $\tau = 1.61 \times 10^{-14} f \lambda \sqrt{\frac{M}{T_D}} N_{\rm ion} L = \beta N_{\rm ion} L$ where f denotes the oscillator strength and λ wavelength, M atomic mass, T_D temperature, $N_{\rm ion}$ ion density, and L path length. Next, the product $N_{\rm ion} L$ can be expressed in terms of the volume emission measure VEM $= N_e^2 L A$, where N_e denotes the electron density and A the area of the assumed cylindrical emission region. N_e and $N_{\rm ion}$ are related through $N_{\rm ion} = 0.85 N_e A_{\rm ion}$, where $A_{\rm ion}$ denotes the abundance of the considered ion relative to hydrogen, assumed to be 3.18×10^{-4}. We thus obtain VEM$= \tau \frac{N_e A}{0.85 A_{\rm ion} \beta}$. In Fig. 4 we plot (assuming $\tau = 1$ and 0.5) A as a function of N_e; note that this curve moves up for τ-values below unity. Since the area shown is bounded above by (half) the stellar surface, we also plot a shaded area corresponding to surface filling factors of accretion hot spots between 0.5 and 0.05. If these filling factors are indeed of the order of a few percent as usually assumed for cTTS, it is clear that densities in excess of 10^{12} cm^{-2} are required to account for both the observed emission measure in TW Hya as well as the absence of any clear optical depth effects.

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References

Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197

Balucinska-Church, M., & McCammon, D. 1992, ApJ, 400, 699

Bhatia, A. K., & Saba, J. L. R. 2001, ApJ, 563, 434

Brown, G. V., Beiersdorfer, P., Chen, H., Chen, M. H., & Reed, K. J. 2001, ApJ, 557, L75

Feigelson, E. D., & Montmerle, T. 1999, ARA&A, 37, 363

Gabriel, A. H., & Jordan, C. 1969, MNRAS, 145, 241

Gu, M. F. 2003, ApJ, 582, 1241

Kastner, J. H., Huenemoerder, D. P., Schulz, N. S., Canizares, C. R., & Weintraub, D. A. 2002, ApJ, 567, 434

Mauche, C. W., Liedahl, D. A., & Fournier, K. B. 2001, ApJ, 560, 992

Ness, J.-U., & Wichmann, R. 2002, AN, 323, 129

Ness, J.-U., Schmitt, J. H. M. M., Audard, M., Güdel, M., & Mewe, R. 2003, A&A, 407, 347

Ness, J.-U., Güdel, M., Schmitt, J. H. M. M., Audard, M., & Telleschi, A. 2004, A&A, 427, 667

Schmitt, J. H. M. M., Robrade, J., Ness, J.-U., Favata, F., & Stelzer, B. 2005, A&A, 432, L35

Smith, R. K., Brickhouse, N. S., Liedahl, D. A., & Raymond, J. C. 2001, ApJ, 556, L91

Stelzer, B., & Schmitt, J. H. M. M. 2004, A&A, 418, 687

Testa, P., Drake, J. J., Peres, G., & DeLuca, E. E. 2004, ApJ, 609, L79