Protostars & Planets VI

Hamburger Sternwarte

DN Tau - a young low-mass CTTS in X-rays

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We present a deep *XMM-Newton* observation of DN Tau, a M0 type classical T Tauri star (CTTS) and extend the sample of young accreting stars studied with high-resolution X-ray spectroscopy to lower masses. We detect X-ray emission from magnetic activity and accretion shocks. DN Tau's X-ray properties link it to more massive and older CTTS. The strong hot corona makes DN Tau one of the X-ray brightest CTTS in its mass range, while the low mass and large radius result in a very cool accretion component and thus reduces its imprint in the observed X-ray spectrum and emission line diagnostics.

The target: DN Tau

Stellar parameter

Sp. type	M 0 [1,2,3]	
$T_{\rm eff}$	3800 [3] ... 3850 [1]	K
M_*	0.38 [1,2] ... 0.52 [3]	$M_\odot$
R_*	2.09 [2]	$R_\odot$
$L_{\rm bol}$	0.87 [2] ... 1.0 [1]	$L_\odot$
A_V	0.25 [2] ... 0.49 [1]	mag
$\log \dot{M}_{\rm acc}$	-7.79 [3] ... -8.46,[2]	$M_\odot yr^{-1}$

[1] Kenyon & Hartmann (1995),, [2] Gullbring et al. (1998, [3] White & Hillenbrand (2004)

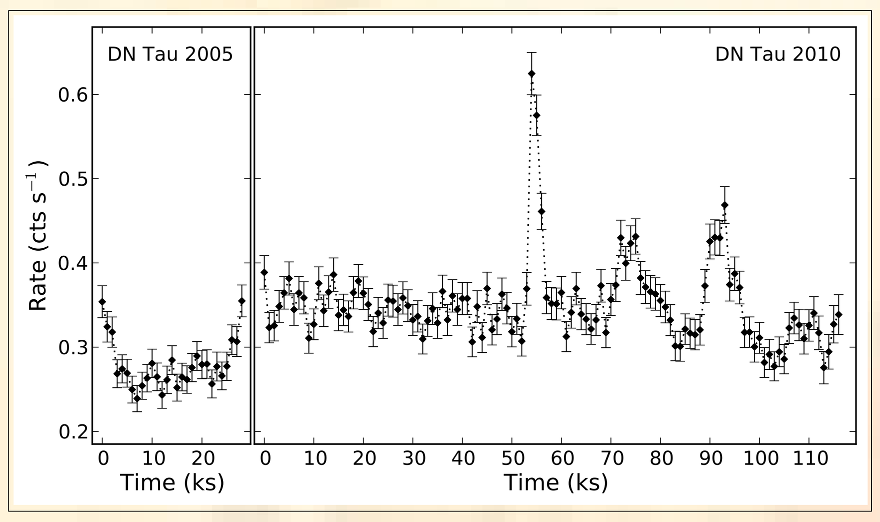
- single star, age: 0.5 – 1.1 Myr (Gullbring et al. 1998, Telleschi et al., 2007)
- viewed under moderate inclination ($i \approx 35^\circ$) (Muzerolle et al., 2003)
- large magnetic field of 2 kG (Johns-Krull, 2007)
- $P_{\rm rot} = 6.3$ d, $V sini = 12.3$ km s^{-1} (Vrba et al., 1993; Nguyen et al., 2012)
- photometric variable, large spot coverage (Bouvier et al., 1986)
- moderate accretor, but highly variable $EWH_\alpha = 12 - 87$ Å
- quite massive disk, close inner rim (Muzerolle et al., 2003; Andrews & Williams 2005)
- X-ray detected by *Einstein* and *ROSAT* (Walter & Kuhi 1981; Neuhäuser et al. 1995)
- *XMM-Newton*: XEST source (No. 12-040) (Güdel et al., Telleschi et al., 2007)
- X-ray brightness variations (factor three) on decades timescale
- low $N_{\rm H}$ and low M_*/R_*
  ⇒ ideal for X-ray studies of young, inflated low-mass CTTS

XMM-Newton observations

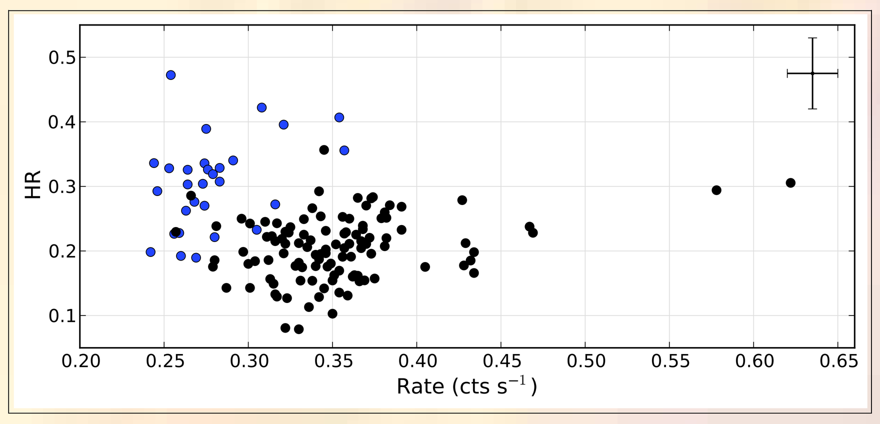
- 120 ks, August 2010 (PI: Robrade)
- 30 ks, March 2005 (PI: Guedel)
- simultaneous UV coverage (UVW1/U filter)

X-ray properties of DN Tau in brief

- DN Tau is X-ray bright, $\log L_{\rm X} = 30.2$ erg s^{-1}
- active corona, hot plasma dominates
- accretion shock signatures pronounced in cool plasma
- strongest variability in cooler plasma components
- no abnormal X-ray absorption ($N_{\rm H}$ consistent with A_V)
- several flares, abundances show IFIP-effect

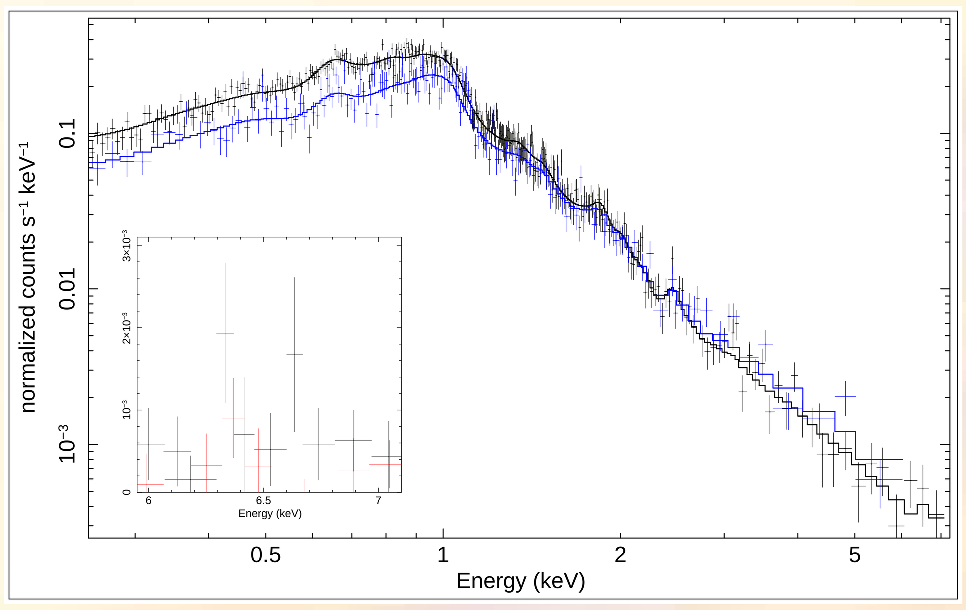


X-ray light curves of DN Tau, 0.2 – 5.0 keV



Hardness ratio of DN Tau, 2010 (black), 2005 (blue).

- $HR = (H - S)/(H + S)$ with S: 0.2 – 0.8 keV, H: 0.8 – 5.0 keV
- fainter state 2005 is overall harder



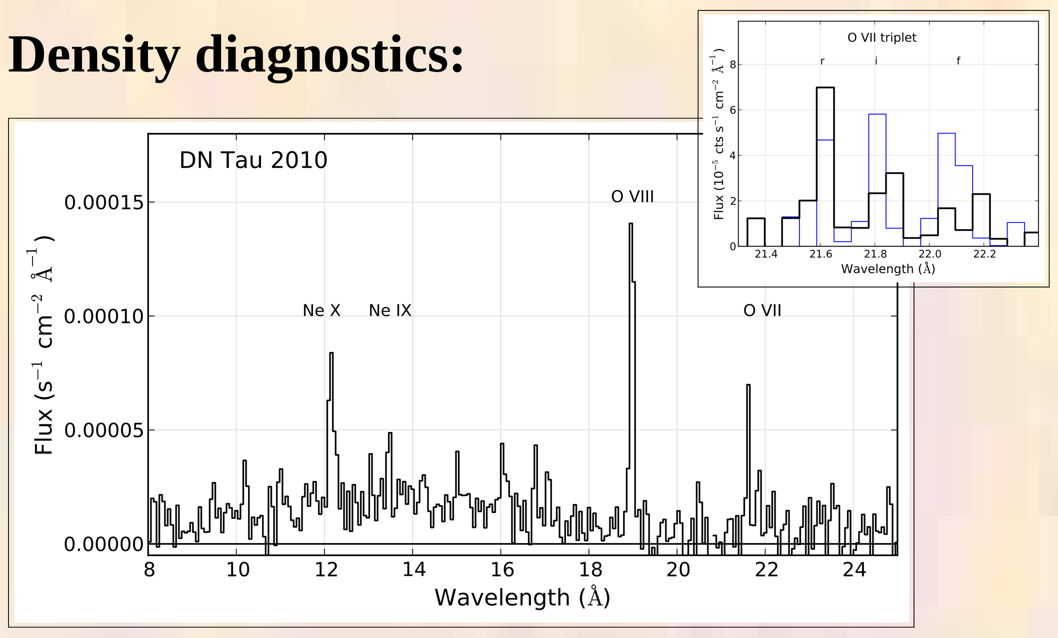
X-ray spectra of DN Tau, PN data+model 2010 (black), 2005 (blue). *Inset:* **Active ($t \geq 55$ ks, black) and quasi-quiescent (red) half of the 2010 observation with possible contributions from Fe Kα (6.4 keV) and Fe XXV (6.7 keV).**

Spectral fit results and 90 % conf. range, MOS data; FIP *(First Ionization Potential)* per element, GrSa98, $L_{\rm X}$ emitted (observed) value.

Par.	2005	2010	unit
$N_{\rm H}$	$0.8^{+0.1}_{-0.1}$		10^{21}cm^{-2}
kT1	$0.17^{+0.05}_{-0.03}$	$0.23^{+0.03}_{-0.03}$	keV
kT2	$0.60^{+0.07}_{-0.06}$	$0.64^{+0.03}_{-0.03}$	keV
kT3	$2.27^{+0.33}_{-0.21}$	$1.91^{+0.15}_{-0.14}$	keV
EM1	$0.8^{+0.9}_{-0.5}$	$2.0^{+0.6}_{-0.5}$	10^{52}cm^{-3}
EM2	$3.7^{+0.5}_{-0.4}$	$5.6^{+0.5}_{-0.6}$	10^{52}cm^{-3}
EM3	$6.4^{+0.6}_{-0.5}$	$5.3^{+0.5}_{-0.4}$	10^{52}cm^{-3}
Mg (7.6 eV)	$0.52^{+0.26}_{-0.18}$		solar
Fe (7.9 eV)	$0.35^{+0.12}_{-0.10}$		solar
Si (8.2 eV)	$0.32^{+0.14}_{-0.12}$		solar
S (10.4 eV)	$0.24^{+0.18}_{-0.17}$		solar
O (13.6 eV)	$0.65^{+0.28}_{-0.16}$		solar
Ne (21.6 eV)	$1.51^{+0.49}_{-0.38}$		solar
χ^2_{red}(d.o.f.)	1.05 (432)		
$L_{\rm X}$ (0.2-5.0 keV)	1.32 (1.00)	1.62 (1.13)	10^{30} erg s^{-1}

Accretion shock signatures

Density diagnostics:

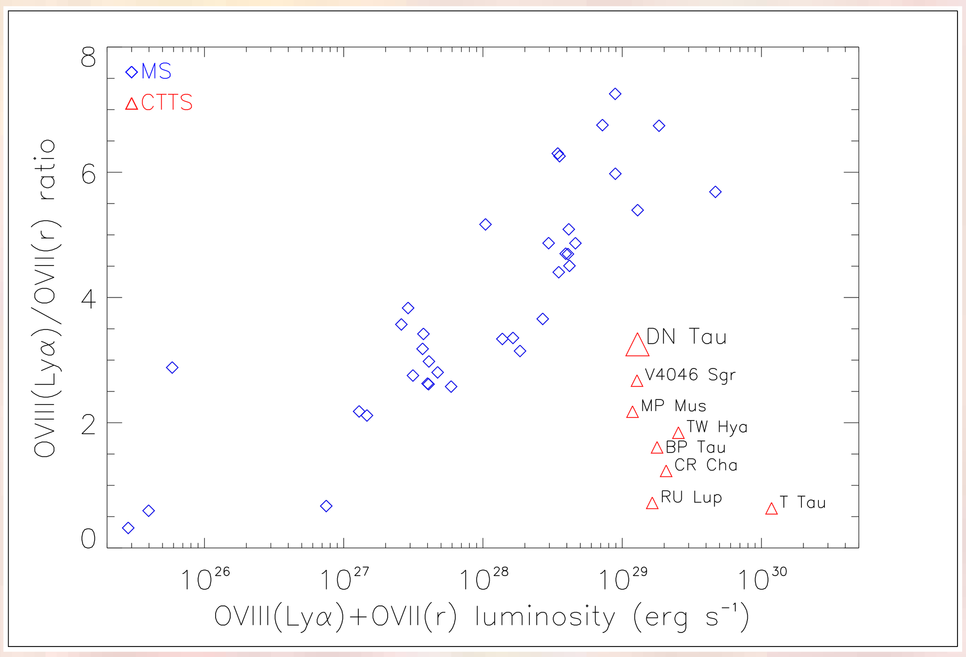


RGS spectrum (2010, 8 – 25 Å).
Zoom: **O VII -triplet in 2010** *(black)* **and 2005** *(blue)*.

The CTTS f/i-ratios in He-like triplets are sensitive to density, high density plasma ($f/i \lesssim 1$) for O VII indicates contributions from accretion shocks.

- O VII traces cool (2 MK) plasma regime
- $f/i = 0.36 \pm 0.26$ (2010) and $f/i = 0.92 \pm 0.73$ (2005)
- $n_e = 3.0\ (1.6 - 11.8) \times 10^{11}$ cm^{-3} (2010) and $n_e = 1.0\ (0.4 - 6.1) \times 10^{11}$ cm^{-3} (2005), neglecting FUV photons
- high density plasma from accretion shock in O VII
- corona quite faint at low temperatures
- upper limit from Ne IX consistent

Temperature diagnostics:

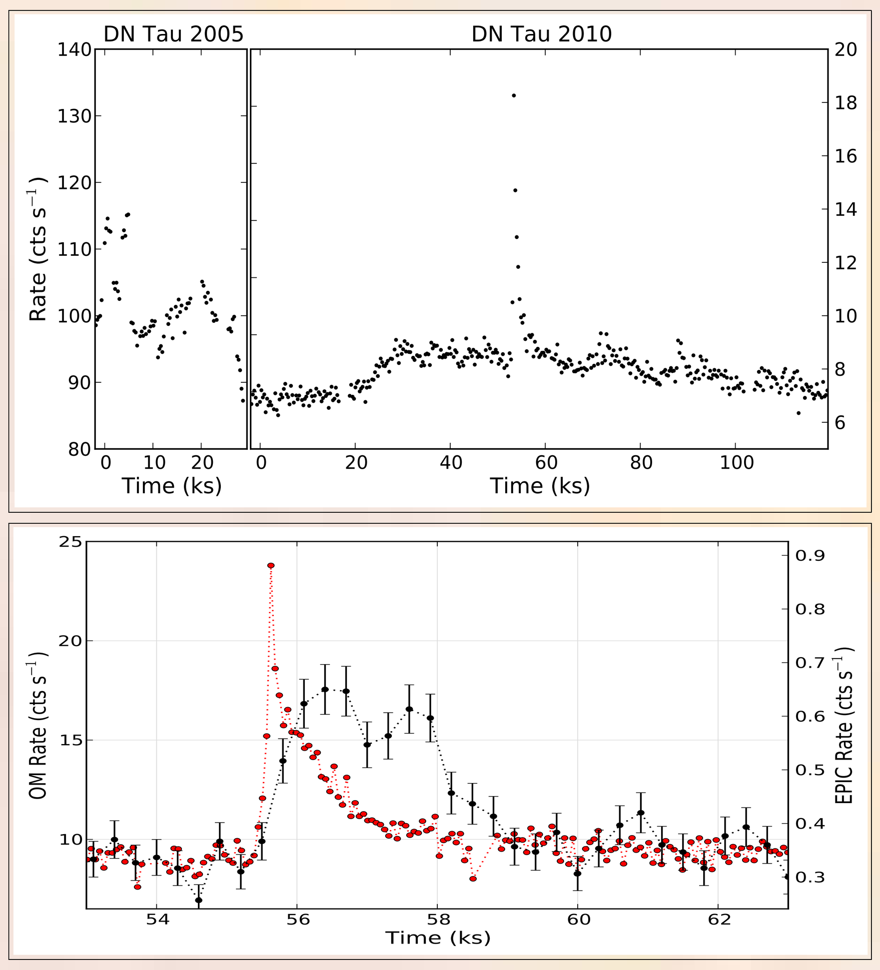


The soft excess of DN Tau.

Ratio of the O VIII / O VII line flux vs. summed luminosity for main-sequence stars (diamonds) and CTTS (triangles); shock-heated material with $V_{\rm sh} \sim 250 \ldots 600$ km s^{-1} produces only cool plasma that predominantly emits at softer X-rays.

- O VIII / O VII line ratio vs. summed luminosity
- traces cool (1 – 5 MK plasma), abundance-independent
- soft excess present on DN Tau
- weakest soft excess of all studied CTTS
  - young low-mass object → small M/R
  - $T_{sh} \propto V_{sh}^2$ and $V_{sh} \propto \sqrt{M_*/R_*}$

X-ray/UV correlation



Top: **OM light curves** (2005, U: $\lambda_{\rm eff}$ 3440 Å; 2010, UVW1: $\lambda_{\rm eff}$ 2910 Å). *Bottom:* **The largest 2010 flare in X-rays (black, 300 s binning) and UV (red, 60 s binning).**

- X-ray flares are accompanied by clear UV counterparts
- UV emission precedes the X-rays → chromospheric evaporation
- no general correlation between X-ray and UV brightness on longer timescales (hours to days)

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