The enigmatic young brown dwarf binary FU Tau: accretion and activity

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ABSTRACT

FU Tau belongs to a rare class of young, wide brown dwarf binaries. We have resolved the system in a *Chandra* X-ray observation and detected only the primary, FU Tau A. Hard X-ray emission, presumably from a corona, is present but, unexpectedly, we also detect a strong and unusually soft component from FU Tau A. Its X-ray properties, so far unique among brown dwarfs, are very similar to those of the T Tauri star TW Hya. The analogy with TW Hya suggests that the dominating soft X-ray component can be explained by emission from accretion shocks. However, the typical free-fall velocities of a brown dwarf are too low for an interpretation of the observed X-ray temperature as a post-shock region. On the other hand, velocities in excess of the free-fall speed are derived from archival optical spectroscopy, and independent pieces of evidence for strong accretion in FU Tau A are found in optical photometry. The high X-ray luminosity of FU Tau A coincides with a high bolometric luminosity confirming an unexplained trend among young brown dwarfs. In fact, FU Tau A is overluminous with respect to evolutionary models while FU Tau B is on the 1-Myr isochrone suggesting non-contemporaneous formation of the two components in the binary. The extreme youth of FU Tau A could be responsible for its peculiar X-ray properties, in terms of atypical magnetic activity or accretion. Alternatively, rotation and magnetic field effects may reduce the efficiency of convection which in turn affects the effective temperature and radius of FU Tau A, shifting its position in the Hertzsprung–Russell diagram. Although there is no direct proof of this latter scenario so far, we present arguments for its plausibility.

Key words: accretion, accretion discs – stars: activity – brown dwarfs – stars: pre-main-sequence – X-rays: stars.

1 INTRODUCTION

The young binary brown dwarf (BD) FU Tau has aroused interest in the star formation community for two particular aspects, both having important implications for BD formation theories (see Luhman et al. 2009a): (1) it is one of only a handful of known binary BDs with wide separation (800 au) and (2) it is located in the B215 dark cloud in Taurus that hosts only one other T Tauri star (TTS). It is the only young (<5-Myr) BD known in such a remote location and therefore it has formed most likely in isolation and not in a stellar cluster or aggregate. From low-resolution optical spectra, Luhman et al. (2009a) measured spectral types of M7.25 and M9.25 for the two components FU Tau A and FU Tau B, respectively. They derive masses of 0.05 and 0.015 $M_\odot$, respectively, comparing the position of the two BDs in the Hertzsprung–Russell (HR) diagram to pre-main-sequence (pre-MS) evolutionary models by Baraffe et al. (1998) and Chabrier et al. (2000). They find that FU Tau A is signif-

icantly overluminous relative to the youngest (1-Myr) isochrone of the models. The extinction was measured from infrared (IR) photometry to be ~2 mag for the primary and <1 mag for the secondary. The spectral energy distributions of both binary components indicate the presence of circumstellar discs by excess emission over the photospheric model in the *Spitzer* mid-IR bands. In addition, there is a blue excess for FU Tau A that might indicate ongoing accretion. Both FU Tau A and B have strong Hα emission in low-resolution spectra [equivalent widths (EW) of 93 and 70 Å, respectively], again a likely accretion signature.

Widely separated BDs are important calibrators of sub-stellar magnetic activity because they allow us to examine the X-ray characteristics of two presumably coeval targets with different (sub-)stellar properties ($T_{\rm eff}$, $L_{\rm bol}$, etc.) in a critical parameter range. Magnetic activity (as probed by Hα and X-ray luminosity) seems to decay strongly at late-M spectral types (Mohanty, Jayawardhana & Basri 2005; Stelzer et al. 2006). *Chandra* is the only X-ray instrument capable of resolving FU Tau and similar BD binaries. In an earlier study we have resolved the wide BD binary in the Chamaeleon
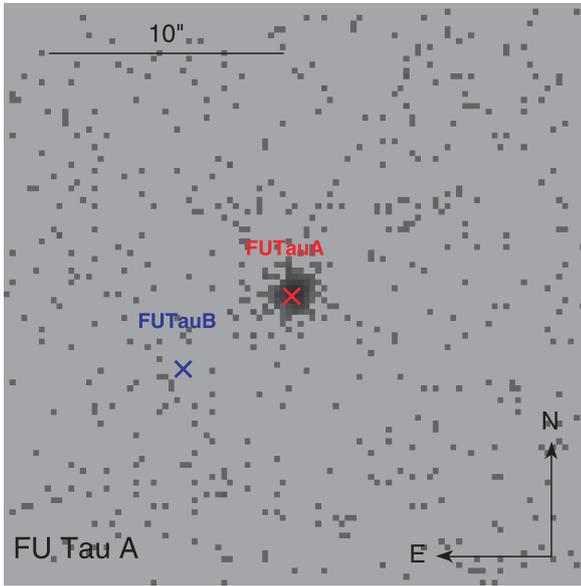
Figure 1. *Chandra*/ACIS image of the FU Tau binary. 2MASS positions are marked with crosses. The secondary is not detected.

star-forming region, 2MASS J11011926−7732383 AB (Stelzer & Micela 2007). In a continuation of our search for coronal activity in sub-stellar twins, we have obtained a *Chandra* X-ray observation of FU Tau. Here we combine the analysis of the X-ray data with archival optical spectroscopy and photometry. The primary turns out to have unexpected X-ray properties. This observation shows how incomplete our knowledge of the high-energy emission of BDs is.

2 DATA ANALYSIS AND RESULTS

2.1 X-ray observation

On 2009 October 22, FU Tau was observed for 55 ks with *Chandra*/Advanced CCD Imaging Spectrometer (ACIS-S) (Obs ID 10984). The data analysis was carried out with the CIAO package,[1] version 4.1; we started with the level-1 event file provided by the *Chandra* X-ray Center. The steps performed to convert these data to a level-2 event file are described e.g. in Stelzer & Micela (2007).

The X-ray image is almost devoid of X-ray sources, not unexpectedly as high extinction through the B215 cloud obscures the background sky. However, bright X-ray emission is found to co-incide with the Two-Micron All-Sky Survey (2MASS) position of FU Tau A. For detecting the X-ray source(s) associated with the two components of the BD binary, source detection was restricted to a 100×100-pixel wide image (1 pixel = 0.5 arcsec) and a congruent, monochromatic exposure map for 1.5 keV centred on the 2MASS position of FU Tau A. Source detection was carried out with the WAVDETECT algorithm with wavelet scales between 1 and 8 in steps of $\sqrt{2}$. We tested a range of detection significance thresholds and found that $\sigma_{th} = 10^{-5}$ avoided spurious detections and at the same time separated close emission components. The X-ray image in the region around FU Tau A is shown in Fig. 1. There is only one X-ray source in the surroundings of the BD binary. It is associated with FU Tau A. The companion FU Tau B remains undetected.

Table 1. X-ray parameters of the FU Tau binary.

Object	Offax (arcmin)	Counts in 0.3–8 keV	Expo (s)	$\log L_x$ (erg s^{-1})	$\log\left(\frac{L_x}{L_{bol}}\right)$
FU Tau A	0.29	603.8 ± 24.6	54153	29.7	−3.2
FU Tau B	0.39	<4.7	54053	<27.2	< −3.8

Note. Bolometric luminosities from Luhman et al. (2009a).

We calculated the source count rates in the following way. A circular source photon extraction region was defined as the area that contains 95 per cent of the point spread function at the position of FU Tau A. The background was extracted individually from a squared region centred on the source extraction area and several times larger than the latter one. A circular area centred on the position of the X-ray source was excluded from the background area. The signal-to-noise ratio (S/N) was computed from the counts summed in the source and background areas after applying the appropriate area scaling factor to the background counts. In practice, the background is very low (a fraction of a count in the source extraction area). Finally, the count rate of FU Tau A was obtained using the exposure time at the source position extracted from the exposure map. We have estimated a 95 per cent confidence upper limit for the count rate at the position of FU Tau B using the algorithm of Kraft, Burrows & Nousek (1991).

In Table 1, we summarize some X-ray parameters of the binary. The distance assumed for the estimate of luminosities is 140 pc. For FU Tau A we report the value of L_x extracted from its spectrum (see below), while for FU Tau B we used Portable Interactive Multi-Mission Simulator (PIMMS)[2] to convert the count rate upper limit to a flux limit. This conversion depends on the unknown spectral parameters. The value given in Table 1 refers to an assumed $N_H = 2 \times 10^{21}$ cm^{-2} (corresponding to the upper limit measured for the A_V of FU Tau B) and $kT = 1$ keV (as typical for a coronal plasma). Note that the influence of N_H on the count-to-flux conversion is much stronger than that of the temperature.

For FU Tau A, a light curve was extracted and searched for variability with a maximum likelihood method that divides the sequence of photons in intervals of a constant signal (see Stelzer et al. 2007a) and, independently, with the Kolmogorov–Smirnov (KS) test. There is no significant variability in the X-ray count rate of FU Tau A (KS-test probability is 0.34) such that the bright emission cannot be attributed to a flare.

The high signal has allowed us to fit the X-ray spectrum of FU Tau A. An individual response matrix and auxiliary response were extracted for the position of FU Tau A using standard CIAO tools. As mentioned above, the background of ACIS is negligibly low. We fitted the spectrum, rebinned to a minimum of 15 counts per bin, in the XSPEC 12.5.0 environment with a one-temperature (1-T) or two-temperature (2-T) thermal model subject to absorption. The spectrum of FU Tau A can be described by an absorbed 2-T thermal model (see Table 2 for the best-fitting parameters). For standard extinction laws (e.g. Predehl & Schmitt 1995) the observed X-ray absorption, N_H, is compatible with the extinction of $A_V = 2$ mag measured in the IR.

In summary, with more than 600 counts the *Chandra* observation of FU Tau A represents the highest quality X-ray data obtained so far for a (young) BD. The most remarkable fact is that the emission is dominated by a cool plasma component of

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[1] CIAO is made available by the *Chandra* X-ray Center and can be downloaded from http://cxc.harvard.edu/ciao/download/

[2] PIMMS is accessible at http://cxc.harvard.edu/toolkit/pimms.jsp

Table 2. X-ray spectral parameters of the absorbed 2-T APEC model for FU Tau A compared to those of TW Hya.

Object	Instrument	$\chi^2_{\rm red}$ (d.o.f.)	$\log N_{\rm H}$ (cm^{-2})	kT_1 (keV)	kT_2 (keV)	$\log EM_1$ (cm^{-3})	$\log EM_2$ (cm^{-3})	$\log L_{\rm x}$[a] (erg s^{-1})
FU Tau A	*Chandra*/ACIS	0.9 (27)	$21.8^{21.9}_{21.5}$	$0.24^{0.34}_{0.19}$	$1.12^{1.28}_{0.99}$	$52.9^{53.5}_{52.1}$	$52.3^{52.4}_{52.2}$	29.5
TW Hya[b]	*XMM–Newton*/EPIC-pn	2.3 (216)	20.8	0.23	1.22	53.0	52.2	29.8

[a]Intrinsic X-ray luminosity in the 0.5–2.0 keV passband; distance assumed for TW Hya is 51 pc (Mamajek 2005).
[b]The best-fitting model of TW Hya has peculiar abundances (not listed here); abundances have been set for all elements to 0.2 solar for FU Tau A because of the low photon statistics.
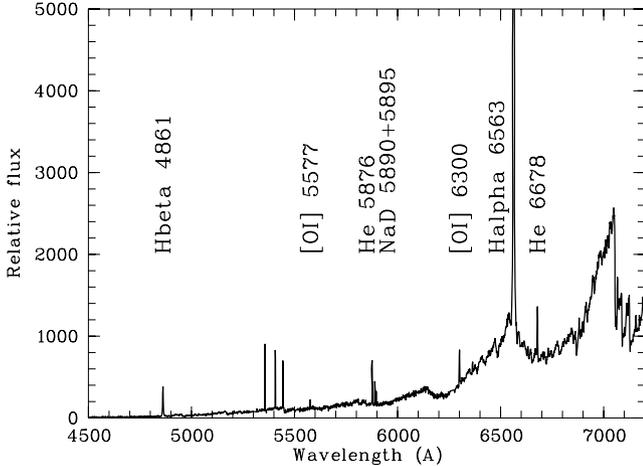

Figure 2. Optical spectrum of FU Tau A from Gemini/GMOS, dominated by Hα emission and with several other prominent emission lines indicative of accretion and/or outflow. The three features between 5300 and 5500 Å are of telluric origin.

temperature $kT = 0.24$ keV. The soft plasma has four times more emission measure (EM) than the hotter component that has a typical coronal temperature (1.1 keV). The X-ray luminosities of the cool and hot components are $\log L_{\rm x,1}$ (erg s^{-1}) $= 29.5$ and $\log L_{\rm x,2}$ (erg s^{-1}) $= 29.2$, respectively, at 0.3–8.0 keV.

2.2 Optical spectroscopy

FU Tau A was observed with Gemini-North and GMOS in a long-slit mode as part of science programme GN-2008A-Q-94, PI Thomas Dall. The data were taken in 2008 March and are publicly available from the Gemini Science Archive. Two spectra have been obtained, one with grism R600 (exposure time of 1200 s, resolution $R \sim 4000$, March 1) and the other with grism B1200 (1200 s, $R \sim 4000$, March 16). In both cases, a 0.5-arcsec slit has been used. The quoted values for the resolution are taken from the Gemini website. To our knowledge, this source has never been observed with a higher spectral resolution. For comparison, the spectra used by Luhman et al. (2009a) have $R < 1000$ (at 6000 Å).

We downloaded the science and calibration files from the Gemini archive and performed standard reduction using the Gemini/GMOS package in IRAF following the GMOS 'cookbook'.[3] This includes bias subtraction, flat-field correction, wavelength calibration, sky subtraction and extraction. Since we are only interested in emission lines, we did not carry out a flux calibration. The final reduced R600 spectrum is shown in Fig. 2 with the most prominent emission lines

[3] http://www.gemini.edu/sciops/data/IRAFdoc/gmosinfospec.html

marked. The B1200 spectrum does not contain Hα and has in general a lower S/N.

The Hα line is broad with an EW of 146 Å, which is higher than the values published by Luhman et al. (2009a). However, EWs are highly sensitive to the chosen value for the continuum and the integration range (Stelzer, Scholz & Jayawardhana 2007b). For a rough assessment of the Hα strength in FU Tau A and its comparison to other objects, we calculate the $L_{\rm H\alpha}/L_{\rm bol}$ ratio. We avoid using the stellar radius in our estimate because of its uncertainties in the case of FU Tau A (see the discussion in Section 3.5). Estimating the continuum flux from the model and with $F_{\rm bol} = \sigma T_{\rm eff}^4$ for the bolometric flux, we find $L_{\rm H\alpha}/L_{\rm bol} = EW \times F_{\rm cont}/F_{\rm bol} \sim 2 \times 10^{-3}$.

We measure a 10 per cent width (Mohanty et al. 2005) of 352 km s^{-1} for the Hα line. The Hα profile is not well resolved; therefore, this value has to be seen as an upper limit. Still, both the EW and the 10 per cent width are clearly above the typically adopted thresholds between non-accretors and accretors of 10 Å and 200 km s^{-1}. Moreover, FU Tau A features a variety of other emission lines which are often seen in accretors, e.g. Hβ, He 5876, He 6678 (Jayawardhana et al. 2006). Thus, the optical spectroscopy clearly confirms FU Tau A as an accreting object. The [O I] 6300 and NaD feature may also be related to outflow/accretion activity, but contamination by telluric emission cannot be excluded.

From the 10 per cent width and based on the correlation given by Natta et al. (2004), we derived an accretion rate of $\dot{M}_{\rm H\alpha} = 3.5 \times 10^{-10}$ M$_\odot$ yr^{-1}. Another estimate for the accretion rate can be obtained based on the line flux in He 5876 and the correlation published by Herczeg & Hillenbrand (2008). In this line, we measure EWs of 10 and 11 Å in the two spectra, i.e. no significant variability is present. Scaling with the continuum flux, which is obtained from the AMES-DUSTY model spectrum for $T_{\rm eff} = 2800$ K and $\log g = 3.5$ (Allard et al. 2001), this gives a line flux of $\log F_{5876}$ (erg cm^{-2} s^{-1}) $= 5.4$, which translates into an accretion rate of $\dot{M}_{\rm He I} = 7.5 \times 10^{-10}$ M$_\odot$ yr^{-1}. Adopting equation (8) of Gullbring et al. (1998), the observed $\dot{M}_{\rm He I}$ can be converted into the accretion luminosity, $L_{\rm acc,He I}$. With an assumed inner disc truncation radius $R_{\rm in} = 2R_*$, the measured $\dot{M}_{\rm He I}$ corresponds to $L_{\rm acc,He I} = 1.2 \times 10^{30}$ erg s^{-1}. Our estimate assumes zero veiling in the continuum (see Mohanty et al. 2005); the actual accretion rate could therefore be slightly higher. Note that $\dot{M}_{\rm He I}$ is higher than $\dot{M}_{\rm H\alpha}$ but compatible within the uncertainties given by the empirical relations (∼0.5 logarithmic dex). The agreement with the accretion rates determined from He 5876 indicates that the large 10 per cent width of the Hα line is intrinsic, i.e. the line is probably resolved.

3 DISCUSSION

3.1 X-ray emission from young BDs

A systematic survey of X-ray emission from BDs in the Taurus star-forming region has been performed by Grosso et al. (2007). They

used data from the *XMM–Newton* Extended Survey of the Taurus Molecular Clouds (XEST; Güdel et al. 2007) that included 17 young BDs. An X-ray detection fraction of 53 per cent was obtained for this sample. Only a small subset of the XEST BDs had enough photons collected (>100 counts) to enable a spectral analysis. For most of them, the statistics was so poor that the spectral shape could be represented adequately with a moderately absorbed ($N_{\mathrm{H}} < 10^{22}\,\mathrm{cm}^{-2}$) 1-T thermal model of $kT \sim 0.5, \ldots, 1.5\,\mathrm{keV}$, typical for the plasma in a magnetically heated corona.

For none of the BDs detected in XEST the X-ray emission is nearly as soft as for FU Tau A, despite that they all have a similar or lower absorbing column favouring the detection of a cool plasma component. Recall that in FU Tau A, the X-ray EM and flux of the cooler spectral component exceed those of the hotter one (see Section 2.1). Dominating soft X-ray plasma has been detected so far only in older BDs, e.g. the evolved BD Gl 569 B has an EM-weighted mean temperature of $kT = 0.6\,\mathrm{keV}$ at an age of 100 Myr (Stelzer 2004) and the 500-Myr-old LP 944-20 had 0.3 keV (Rutledge et al. 2000). Both of them were detected during a flare, i.e. in an event known to go along with plasma heating, and their quiescent emission – if any – is probably even softer. The decrease of $L_{\mathrm{x}}/L_{\mathrm{bol}}$ and kT of BDs with age has tentatively been explained by reduced coronal heating related to the increasingly cool effective temperatures (Stelzer et al. 2006).

In the 0.5–8 keV band, used by Grosso et al. (2007) for XEST, the X-ray luminosity of FU Tau A ($4 \times 10^{29}\,\mathrm{erg\,s}^{-1}$) is at the high end of that of all BDs in Taurus. In Fig. 3, we show the X-ray luminosity of the two components in the FU Tau binary compared
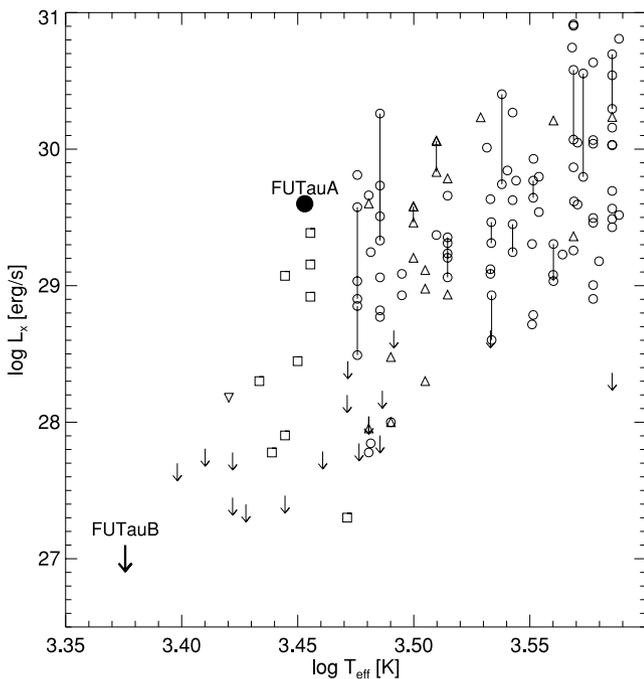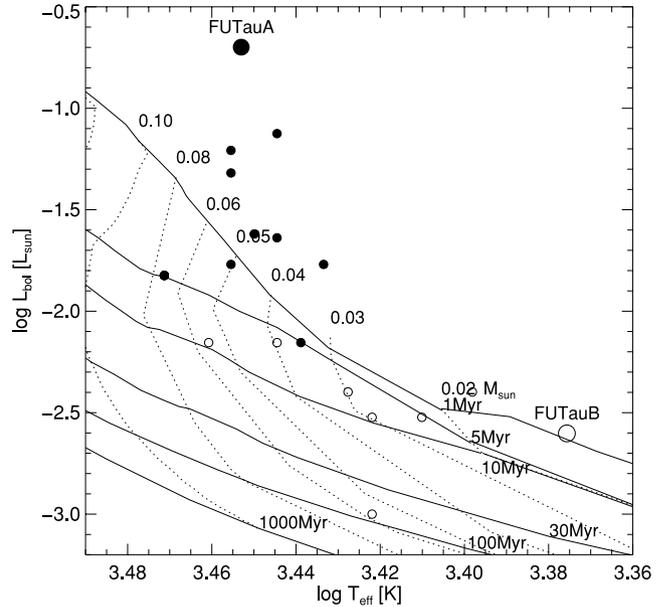

Figure 4. HR diagram for VLM objects in Taurus including BDs from Grosso et al. (2007) and the FU Tau binary on pre-MS models from Baraffe et al. (1998) and Chabrier et al. (2000). X-ray detections are shown as filled circles; non-detections are open circles.

to other BDs and TTSs in Taurus. Note that we plot the total X-ray luminosity for FU Tau A, although below we argue that possibly only the weaker, hot component is of coronal origin. If only the hotter spectral component of FU Tau A, which is more similar to the plasma detected from other Taurus BDs, is considered, FU Tau A is still the X-ray brightest BD in Taurus together with CFHT-BD-Tau 4. The data for the BDs were extracted from Grosso et al. (2007); those for the TTS are from the catalogue of Güdel et al. (2007). In addition, we add data for new Taurus members identified after the publication of the first results from XEST. The X-ray data for these objects are taken from Scelsi et al. (2007) and Mokler & Stelzer (2002), and their stellar parameters are listed by Luhman et al. (2009b). Recall that contrary to some very-low-mass (VLM) stars with high X-ray luminosities, indicated by vertical lines in Fig. 3, FU Tau A did not show variability.

The fractional X-ray luminosity of FU Tau A ($\log L_{\mathrm{x}}/L_{\mathrm{bol}} = -3.3$ in 0.5–8 keV) is within the range observed for other Taurus BDs. If only the hot spectral component of FU Tau A is considered, $\log(L_{\mathrm{x}}/L_{\mathrm{bol}}) = -3.7$ which is even more typical for young BDs; the median for the XEST BDs is -4.0 according to Grosso et al. (2007). This 'normal' $L_{\mathrm{x}}/L_{\mathrm{bol}}$ ratio despite the high L_{x} is a consequence of the particularly high bolometric luminosity of FU Tau A. Luhman et al. (2009a) give $L_{\mathrm{bol}} = 0.2\,\mathrm{L}_{\odot}$, about a factor of 3 higher than for the optically brightest of the BDs examined by Grosso et al. (2007). Its position more than 1 dex above the youngest isochrone of the evolutionary calculations by Baraffe et al. (1998) can be seen in Fig. 4. While several other BDs in Taurus are located above the 1-Myr isochrone as well, FU Tau A is clearly an extreme case.

3.2 X-ray emission from substellar twins

The components in a binary are usually believed to be coeval. For BD binaries resolvable with *Chandra*, this enables a study of X-ray properties from two substellar objects of different spectral types, i.e. mass. In the common hypothesis that the X-ray emission from BDs

Figure 3. X-ray luminosity versus effective temperature for young stars [circles – Güdel et al. (2007); upward pointing triangles – Scelsi et al. (2007)] and BDs [squares – Grosso et al. (2007); downward pointing triangle – Mokler & Stelzer (2002)] in Taurus and the position of FU Tau. Non-detections in X-rays are indicated by downward pointing arrows. The vertical lines connect the X-ray emission levels for stars observed and detected in two XEST pointings. The luminosities for the TTS given by Güdel et al. (2007) and shown in this figure refer to a slightly broader energy band (0.3–10 keV), but for a typical coronal X-ray spectrum ($kT \sim 1\,\mathrm{keV}$) the difference in flux to the 0.5–8.0 keV band used in the BD study is negligible.

is produced in a corona, this means investigating the temperature and mass dependence of magnetic activity.

We detected the optically brighter primary, FU Tau A, with *Chandra* at more than two decades higher count rate than the upper limit for the undetected secondary. Considering that these two BDs differ by only two spectral subclasses, our result thus implies either (i) a very steep decrease of X-ray activity between spectral types M7 and M9, (ii) a crucial influence of some other parameter on the efficiency of magnetic activity, (iii) a misinterpretation of the link between the two stars or (iv) an altogether different X-ray emission process. Next, these hypotheses are investigated.

Fig. 3, indeed, points at a steep drop in X-ray efficiency around $T_{\rm eff} \sim 2700\,\rm K$. However, the decay of $L_{\rm x}$ goes along with decreasing optical brightness of BDs, and the sensitivity of XEST and our *Chandra* data for FU Tau do not allow us to ascertain whether systematic changes of $L_{\rm x}/L_{\rm bol}$ occur in the substellar regime at the age of Taurus (few Myr).

Extinction is unlikely the reason for the non-detection of FU Tau B because its $A_{\rm V}$ is smaller than that of component A; see however Stelzer et al. (2007a) for the case of the BD binary 2MASS J11011926−7732383 AB where the component with higher $A_{\rm V}$ was brighter in X-rays than that with lower $A_{\rm V}$. Possible parameters that rule magnetic activity are the rotation rate and the magnetic field strength and structure. It was shown that pre-MS stars are in the saturated regime of the activity–rotation relation where $L_{\rm x}$ is independent of rotation (Preibisch et al. 2005; Briggs et al. 2007). While *evolved* VLM stars show little or no X-ray emission despite rapid rotation (Berger et al. 2010), the connection between X-rays and rotation has not yet been examined for *young* objects in the substellar regime. Rotation periods from few hours to several days have been measured for young BDs (e.g. Joergens et al. 2003; Scholz & Eislöffel 2004). Rotation and magnetic field are unexplored for FU Tau; see Section 3.5 for an estimate of both.

Another possibility that would explain the strongly different X-ray emission levels of FU Tau A and B is that the two objects are *not* coeval with the primary being younger and therefore more active. This interpretation is in line with the HR diagram position of FU Tau A *above* the models while FU Tau B coincides with the 1-Myr isochrone. An initial age difference of ≤ 1 Myr would become impossible to recognize within a few Myr. Alternatively, FU Tau A and B may be unrelated objects, with component A being much closer than the assumed 140 pc. This would explain its high X-ray and bolometric luminosity. However, the binary nature of this BD system was established by Luhman et al. (2009a) on the basis of the low probability for a chance projection, especially considering the high extinction through the B215 cloud.

Finally, the different X-ray properties of FU Tau A and B might point at different emission mechanisms in the two objects. In Section 3.3, we suggest that a major part of the X-ray emission from FU Tau A may be related to the accretion process and not a confined corona.

3.3 FU Tau A, a substellar analogue to TW Hya?

In Fig. 5, we display the X-ray spectrum of FU Tau A. As already mentioned in Section 2.1, the spectral fitting revealed an unexpectedly strong soft plasma component. This characteristic is reminiscent of the TTS TW Hya. In Table 2, we compare the best-fitting parameters of FU Tau A to those obtained from an observation of TW Hya with *XMM–Newton's* European Photon Imaging Camera (EPIC). Despite the best-fitting result presented by Stelzer & Schmitt (2004) for TW Hya was a 3-T model, we show here the
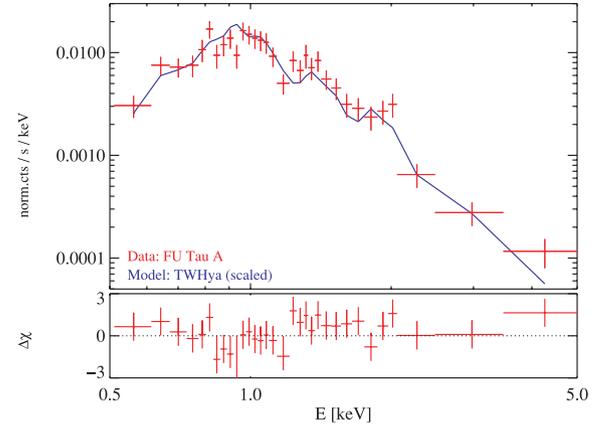

Figure 5. *Chandra*/ACIS spectrum of FU Tau A and residuals with respect to the best fit presented in Table 2 (red in online version) compared to the 2-T best-fitting model for TW Hya (solid line; blue in online version). The spectrum of TW Hya has been scaled by a factor of 0.07 to make the comparison with FU Tau A easier. We also have artificially increased the absorbing column density of TW Hya to the value measured for FU Tau A and reduced the neon abundance from its atypically high value to solar.

parameters for a 2-T model for better comparison with FU Tau A. This model spectrum for TW Hya is overlaid in Fig. 5 on the observed spectrum of FU Tau A. (A direct graphical comparison of the two observations is impossible because of the different instruments with which the data were obtained.) To ease the comparison, the model of TW Hya was multiplied with a factor of 0.07 (accounting for the difference in distance and the factor of 2 difference in X-ray luminosity), the column density was increased to the value observed for FU Tau A and the neon abundance was decreased to the solar level. There is almost a 1:1 correspondence between the spectrum of FU Tau A and the down-scaled, artificially absorbed spectrum of TW Hya, demonstrating that the temperature structure is very similar.

Both objects are dominated by soft emission with only a weak emission component from the higher energy photons that are typical for stellar coronae. By means of high-resolution X-ray spectroscopy, plasma densities ($n_{\rm e} \sim 10^{12}\,\rm cm^{-3}$) 2 dex higher than in stellar coronae have been measured for TW Hya (Kastner et al. 2002; Stelzer & Schmitt 2004). Its soft X-ray emission and the measured high densities are compatible with the conditions in an accretion shock. This way TW Hya was established as the prototype of a pre-MS star with X-ray emission from accretion columns. A handful of other accreting TTSs have since been recognized to display high density X-ray emitting plasmas (e.g. Schmitt et al. 2005; Günther et al. 2006), and an excess of soft X-rays over the typical coronal emission of young stars has been detected in a number of accreting TTSs (Güdel & Telleschi 2007). Obtaining a high-resolution X-ray spectrum for FU Tau A or any other BD is out of reach for present-day X-ray instrumentation, such that its plasma density cannot be constrained. However, on the basis of the similar temperature structure between the X-ray spectrum of FU Tau A and TW Hya we speculate that the soft X-ray emission from FU Tau A, represented by the dominating component 1 in the spectral fit, may be produced in accretion shocks rather than in a corona.

To check if the accretion scenario is compatible with the observed properties, we compute the theoretically expected EM from the post-shock region:

$$EM_{\rm psh} = \dot{M}_{\rm acc} \times \frac{3k_{\rm B} \times T_{\rm psh}}{\mu m_{\rm p} P(T_{\rm psh})}, \tag{1}$$

where k_B is the Boltzmann constant, $\mu = 0.61$ the mean particle weight in units of the proton mass m_p and $P(T_{psh})$ the radiative loss function extracted from APEC (Smith et al. 2001). The post-shock temperature is $T_{psh} = \frac{3}{16} \frac{\mu m_p}{k_B} v_0^2$, where v_0 is the infall speed. For the accretion rate, $\dot{M}_{acc}$, we substitute the value obtained from He 5876, $\dot{M}_{He\,I}$. Adopting for v_0 the velocities measured from the width of the Hα profile, $v_{Hα} \sim 175 \, \mathrm{km \, s^{-1}}$, we find $kT_{psh} \sim 0.03 \, \mathrm{keV}$ and $\log EM_{psh} (\mathrm{cm^{-3}}) = 52.7$. While the predicted EM is roughly comparable to the soft X-ray plasma, EM_1 from Table 2, the post-shock temperature is smaller than the observed X-ray temperature, kT_1. The thermal emission connected to the low temperature expected from material infalling towards a BD should, indeed, be too soft to be significant in the X-ray band. On the other hand, as discussed in Section 3.1 the dominance of the soft X-ray component is completely untypical for magnetic activity on such a *young* BD. So, if accretion is not responsible for FU Tau A's X-ray emission, it must have a very unusual corona.

3.4 Accretion properties of FU Tau A

FU Tau A stands out among BDs of similar mass for its high accretion rate. The empirical M–$\dot{M}_{acc}$ relation has a large spread of controversial origin. From optical spectroscopy, values of $\dot{M}_{acc} \sim 10^{-12,...,-9} \, \mathrm{M_\odot \, yr^{-1}}$ have been measured for BDs with $M \sim 0.05 \, \mathrm{M_\odot}$ (e.g. Natta, Testi & Randich 2006). However, in that mass range accretors with $\dot{M}_{acc} \geq 10^{-10} \, \mathrm{M_\odot \, yr^{-1}}$ are found only in ρ Oph, the youngest of the examined star-forming sites (Natta et al. 2004), and the M_*–$\dot{M}_{acc}$ relation predicts $\log \dot{M}_{acc} (\mathrm{M_\odot \, yr^{-1}}) = -10.7$, more than 1 dex below our value for $\dot{M}_{He}$.

Strong accretion produces hotspots on the surface of the star that might introduce brightness variations in the course of a rotation cycle. The two epochs of Sloan Digital Sky Survey (SDSS) photometry (from 2002 December 6 and 29) presented by Luhman et al. (2009a), indeed, indicate strong flux variations. The amplitude is 0.07 mag in the z band and increases monotonically towards blue wavelengths (e.g. 0.27 mag in the r band and 0.44 mag in the g band). The wavelength dependence from a standard extinction law (Mathis 1990) is not steep enough to explain this behaviour with variable extinction, and we assume that we see the signature of starspots. Using a simple spot model comparable to the one presented by Scholz, Eislöffel & Froebrich (2005) and assuming blackbody spectra for the spotted and unspotted surface area, we find that cool spots with $\Delta T = 0$–1000 K and filling factor $f = 5$–50 per cent do not provide the observed steep decrease of amplitude with wavelength. On the other hand, hotspots (caused by the accretion flow) with $\Delta T > 500$ K and $f = 5$–10 per cent yield a decent match to the observed spectral dependence of the amplitudes. We assume here that the minimum photometry corresponds to the photosphere which may not be the case. Clearly, the two epochs of SDSS data provide only a lower limit to the variability of FU Tau A. Spots with ΔT of a few 1000 K, as have been measured on other BDs (Scholz et al. 2009), cannot be ruled out for FU Tau A on the basis of existing photometry. Hotspots with these characteristics have a luminosity of $L_{spot} = 1.5 \times 10^{32} \, \mathrm{erg \, s^{-1}}$, i.e. ~20 per cent of the bolometric luminosity of FU Tau A.

3.5 The relation between stellar parameters and accretion/activity in FU Tau A

One puzzling feature of FU Tau A is its position high above the youngest isochrone in the HR diagram. An accurate assessment of

(sub-)stellar parameters is crucial for the evaluation of accretion and X-ray properties as can be seen from the following open problems. First, the velocities derived in Section 3.3 from the Hα line are difficult to reconcile with the free-fall speed for the published (sub-)stellar parameters of FU Tau A. In particular, its large L_{bol} and ensuing huge radius (1.8 R$_\odot$) imply $v_{ff} \sim 100 \, \mathrm{km \, s^{-1}}$, almost a factor of 2 lower than the value derived from Hα. Secondly, the spot luminosity and the luminosity derived from the kinetic energy of the infalling material ($L_{acc,He\,I}$) could be better reconciled assuming a 1-dex fainter L_{bol} for FU Tau A; this would moreover make the BD compatible with the 1-Myr isochrone. On the other hand, the high bolometric luminosity of FU Tau A comes along with high X-ray luminosity, supporting an unexplained trend first noticed by Stelzer & Micela (2007) who found that most of the BDs in star-forming regions detected in X-rays are located on the 1-Myr isochrone or above the evolutionary calculations. This trend is also seen in Fig. 4. Thus, FU Tau A may not be an isolated albeit an extreme case. In the following, we consider various possible causes for the high luminosity of FU Tau A: magnetic activity, accretion, problems with models and wrong distance.

3.5.1 Reduced convection affecting temperature and radius

A mechanism that can produce larger radius (and cooler temperature) for a given mass, without affecting the bolometric luminosity, i.e. shifting the object horizontally in the HR diagram, is reduced convection efficiency and ensuing heat flux because of fast rotation and/or strong magnetic fields. Such a scenario has been investigated by Chabrier, Gallardo & Baraffe (2007) and by MacDonald & Mullan (2009) using different approaches to model the influence of the magnetic field. Both studies have successfully explained the temperature reversal of the eclipsing spectroscopic binary 2MASS J05352184−0546085 (Stassun, Mathieu & Valenti 2007) with strong magnetic effects on the primary. Indeed, in that object the primary, which has a lower effective temperature than the secondary, is strongly active in terms of high rotation velocity and strong Hα emission (Reiners et al. 2007).

Shifting FU Tau A to higher temperatures on to the 1-Myr isochrone in the HR diagram to make up for a presumed effect of activity on T_{eff} and R_* yields a 'true' mass of ~0.2 M$_\odot$ and a 'nominal' temperature of ~3190 K. We can estimate the rotation period and field strength required for magnetospheric accretion models. We adopt the X-wind model that defines the disc truncation radius R_x as the distance from the star where the Keplerian angular velocity equals the stellar angular velocity (see Ostriker & Shu 1995; Mohanty & Shu 2008). Assuming $R_{in} = 2R_*$ we obtain with the radius of 1.83 R$_\odot$ derived from luminosity and temperature and with the 'corrected' stellar mass of FU Tau A a period of $P_{rot} \sim 1.8$ d. Using the model of Koenigl (1991), where the disc truncation radius is smaller than the corotation radius, yields a longer period, $P_{rot} \sim 5$ d. We note in passing that a larger inner disc radius ($R_{in} = 5R_*$ is often used in the literature) yields periods between 7 and 21 d depending on the details of the accretion model. These latter values for the period are at the high end of the values measured for BDs and TTSs (e.g. Scholz & Eislöffel 2004; Herbst et al. 2007). Indeed, Rebull et al. (2006) presented evidence that stars with discs have longer periods on a statistical basis than stars without discs but this does not exclude the existence of (some) fast-rotating accretors. For the observed $\dot{M}_{He\,I}$, Koenigl (1991) predicts for FU Tau A a magnetic field between $B \sim 85$ and 400 G, for assumptions of $R_{in} = 2R_*$ and 5 R$_\odot$, respectively. Magnetic

fields with kG strength are not unusual for the TTSs (Johns-Krull 2007). For BDs with ages of ∼1–10 Myr, Reiners, Basri & Christensen (2009) could not find detectable fields with upper limits of ≤1 kG for all of the accretors, while young but non-accreting BDs and evolved ultracool dwarfs in the field exhibit field strengths of a few kG (Reiners & Basri 2007). However, the sample of only three accretors studied by Reiners et al. (2009) is too small to be clear evidence against the presence of ≤1-kG fields on accreting substellar objects.

To summarize, for a reasonable range of R_{in} we obtain either fast rotation or a strong magnetic field for FU Tau A, i.e. at least one of the two conditions for suppressing convection seems to be fulfilled independent of the position of the disc truncation radius. The high level of (X-ray) activity of FU Tau A – even neglecting the dominating cool X-ray plasma possibly produced by accretion – is compatible with this scenario. Similarly, the high value for the Hα flux corresponds to a high $L_{Hα}/L_{bol}$ ratio. However, given the dominant contribution of accretion in forming the Hα line this measurement cannot be used as a diagnostic for strong magnetic activity in FU Tau A, contrary to the case of the non-accreting eclipsing binary 2MASS J05352184−0546085 (Reiners et al. 2007). Cool star-spots are expected as a manifestation of inhibited convection. As argued in Section 3.4, the two epochs of photometric observations cannot be explained by cool spots alone, but they cannot rule out the presence of cool spots either. More detailed monitoring is required to test this scenario.

While the above considerations are not conclusive, in the absence of measured rotation, field strength and good constraints on the nature of the spots it is not excluded that rotation/fields affect the stellar parameters of FU Tau A. However, the presence of accretion, contrary to the case of 2MASS J05352184−0546085, certainly complicates the situation. A quantitative theoretical evaluation of magnetic field effects in this particular object would certainly provide further insight. We now discuss a few implications of this scenario for the interpretation of our X-ray and Hα observations. First, the higher mass would move FU Tau A into the stellar regime. Higher mass objects have higher X-ray luminosity, i.e. FU Tau A would be less extreme in terms of X-ray brightness. The L_{x}/L_{bol} ratio would be unchanged and it is, indeed, compatible with the values observed in young VLM stars; in the Orion Nebula Cluster the median of 0.2-$M_{\odot}$ stars is $\log(L_{x}/L_{bol}) \sim -3.5$ and the spread is at least 1 logarithmic dex (Preibisch et al. 2005). Secondly, the free-fall velocity would be higher (∼200 km s^{-1}) and in better agreement with the observed Hα profile. Moreover, the higher velocity corresponds to a predicted post-shock temperature which is more similar to the X-ray observed temperature. Finally, the accretion luminosity derived from $\dot{M}_{He}$ would increase by a factor of 4 but still be much smaller than the estimated spot luminosity.

3.5.2 Excess accretion luminosity

Alternatively, the position of FU Tau A and similar objects in the HR diagram may be due to excess luminosity related to accretion. Luhman et al. (2009a) have estimated L_{bol} for FU Tau A from its *J*-band magnitude, where deviations from photospheric emission due to the presence of a disc and accretion are usually smallest. However, strong (accretion) variability in the *J* band cannot be ruled out with the available data.

If the true bolometric luminosity of FU Tau A is significantly lower than the adopted value, the radius is smaller (for given mass of 0.05 $M_{\odot}$) and the free-fall velocity gets larger, e.g. a factor

of 10 smaller L_{bol} gives $v_{ff} = 180$ km s^{-1} in perfect agreement with the observed Hα width. On the other hand, this interpretation implies a high fractional X-ray luminosity for FU Tau A and the other BDs that are located above the models in the HR diagram ($L_{x}/L_{bol} \geq 10^{-3}$). Such high X-ray emission levels are difficult to explain in terms of T Tauri-like activity. Moreover, two of the three Taurus BDs that are closest in the HR diagram to FU Tau A, i.e. highest above the models, are not accreting based on the EW of their Hα emission (Grosso et al. 2007) and they even have no discs according to Luhman et al. (2010), making accretion luminosity an unlikely explanation for their discrepancy with the evolutionary models.

3.5.3 Shortcomings of evolutionary models

It is well known that different sets of pre-MS models are inconsistent among each other and none of them describes adequately all observations. It is not clear to what extent these discrepancies between data and model are due to problems with the stellar parameters derived from observations or due to shortcomings in the theory. Baraffe, Chabrier & Gallardo (2009) showed that the typically observed age spread of 1–10 Myr in the HR diagram for stellar populations in star-forming regions can be explained by episodic accretion during the protostellar phase. However, they cannot explain the presence of objects above the 1-Myr isochrone. These authors suggest that such objects are very young, having experienced their episodic protostellar accretion events quite recently and not yet contracted to the 1-Myr position of non-accreting objects of the same mass. In this view, the two components of the FU Tau binary are not coeval.

An age difference of a few hundred thousand years has been detected for the first time in an equal-mass eclipsing binary, Par 1802, by Stassun et al. (2008), demonstrating that subsequent formation of the components in stellar systems is possible. For the case of FU Tau, the existing evolutionary models are not helpful for constraining the possible age difference. Compared to Par 1802, FU Tau is of lower mass and much wider separation. Moreover, the masses of the two components are not equal introducing additional uncertainties in an evaluation of their evolution. To our knowledge, star formation theories have not yet made predictions on such young non-coeval binaries, their properties and possible influence of the environmental conditions.

3.5.4 Wrong distance or binarity of FU Tau A

Finally, we mention for completeness further scenarios that would reduce the bolometric luminosity of FU Tau A and bring it in accordance with the 1-Myr isochrone, as follows. (i) A much closer distance than assumed; this would also result in a lower, and more typical, X-ray luminosity. However, the ensuing non-binarity with component B is countered by statistical arguments, and distance is unlikely to be responsible for similar cases of other BDs above the evolutionary models. (ii) The primary in the FU Tau system might be a binary; however, this would not provide a solution because it would decrease L_{bol} by at most a factor of 2.

4 SUMMARY

Among the most puzzling features in the enigmatic BD FU Tau A are a very high bolometric luminosity for its effective temperature and its strong and unexpectedly soft X-ray luminosity pointing at an origin in accretion rather than a corona.

Assuming a misinterpretation of the stellar parameters as discussed in Section 3.5 would resolve many open problems: HR diagram position, free-fall versus observed velocities, spectroscopic and photometric accretion luminosities. Suppressed convection as a result of fast rotation and/or strong magnetic field might be responsible for the apparent excess luminosity of FU Tau A with respect to pre-MS evolution calculations. If confirmed, this would be the first case of an *accreting* BD with strong field effects. However, in the absence of observational constraints on the rotation rate and field strength this explanation is not much more than a plausible hypothesis. Keeping in mind the many pieces of evidence for strong accretion in FU Tau A from optical photometry, optical spectroscopy and X-ray emission, it is possible that the excess luminosity may be explained by a significant contribution of accretion to the J magnitude. Further constraints on the accretion properties of this benchmark BD are required to give our estimates a quantitatively sound basis. Last but not least, the existence of other BDs that have stellar parameters incompatible with evolutionary models, albeit less pronounced, may suggest problems with the ages predicted by evolutionary models. If FU Tau A is younger than 1 Myr and not coeval with FU Tau B, as suggested by Baraffe et al. (2009), its extraordinarily strong and soft X-ray emission, irrespective of whether due to accretion or to activity, could then be a result of its young age. In the near future, we aim at further constraining observationally the accretion and activity of this unusual object.

Our *Chandra* observations of FU Tau A represent the first indications for X-ray emission from accretion shocks in a BD (provided FU Tau A *is* a substellar object and not a star as argued in Section 3.5.1). We note that even if free-fall velocity and Hα width of FU Tau A can be reconciled with the scenarios described in Section 3.5, the predicted X-ray post-shock temperature is still lower than our observed value. While this discrepancy remains unexplained, a similar case is represented by the TTS Hen 3-600. This object shows clear evidence of accretion from its Hα characteristics as well as the density and softness of its X-ray emitting plasma (Huenemoerder et al. 2007). However, quantitatively its mass ($0.2\,M_\odot$) and radius ($R = 0.9\,R_\odot$) imply a post-shock temperature of 1.1 MK, to be compared to the measured X-ray plasma temperature of ∼3 MK.

ACKNOWLEDGMENTS

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