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# The origin of X-ray emission from T Tauri stars

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**Abstract.** Several aspects concerning the origin of the very strong X-ray activity of T Tauri Stars (TTS) are still not well understood. Important new insight came recently from the *Chandra* Orion Ultradeep Project (COUP), a unique 10-day long *Chandra* observation of the Orion Nebula Cluster, and the XMM-Newton Extended Survey of the Taurus Molecular Cloud (XEST). Based mainly on the results of these two large projects, I will discuss our current knowledge about the location of the X-ray emitting structures in TTS, the nature of their coronal magnetic fields, inferences for pre-main-sequence magnetic dynamos, and the relation between accretion processes and X-ray emission.

**Key words.** Stars: activity – Stars: magnetic fields – Stars: pre-main sequence – X-rays: stars

## 1. Introduction

T Tauri stars (TTS) are low-mass ($M \leq 2\,M_{\odot}$) pre-main sequence stars with typical ages between $\lesssim$ 1 Myr and a few Myr. They come in two flavors: the classical T Tauri stars (CTTS) show H$\alpha$ emission and infrared excesses, which are a signature of circumstellar disks from which the stars accrete matter. The weak-line T Tauri stars (WTTS), on the other hand, have already lost (most of) their circumstellar material and show no evidence of accretion. TTS generally show highly elevated levels of X-ray activity, with X-ray luminosities up to $\sim 10^4$ times and plasma temperatures up to $\sim$ 50 times higher than seen in our Sun (e.g., Feigelson & Montmerle 1999). This strong X-ray emission has far-reaching implications for the physical processes in the circumstellar environment, the formation of planetary systems, and the evolution of protoplanetary atmospheres (e.g., Glassgold et al. 2005; Wolk et al. 2005).

After the first discoveries of X-ray emission from TTS with the EINSTEIN satellite (e.g., Feigelson & DeCampli 1981), many star forming regions and young clusters have been observed with different X-ray observatories (e.g., Casanova et al. 1995; Gagné et al. 1995; Preibisch, Zinnecker, & Herbig 1996; Feigelson et al. 2002; Preibisch & Zinnecker 2002; Flaccomio et al. 2003). While these observations provided important information about the X-ray properties of TTS, there were also serious limitations. First, the typical samples of X-ray detected objects in each observation contained hardly more than $\sim$ 100 objects, too few to allow well founded statistical conclusions to be drawn. Second, a large fraction of the known cluster members (especially low-mass stars) remained undetected in X-rays, and any correlation studies had therefore to deal with large numbers of upper lim-

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*Send offprint requests to*: Th. Preibisch its. Third, especially in dense clusters, the individual sources could often not be spatially resolved, and so the proper identification of the X-ray sources was difficult or impossible. Finally, in most X-ray data sets, only a relatively small number of individual young stars were bright enough in X-rays to allow their spectral and temporal X-ray properties to be studied in detail, and it was not clear whether these stars really are "typical" cases or perhaps peculiar objects.

The basic, still unresolved question concerns the exact origin of the X-ray activity of TTS. Although there is strong evidence that in most TTS the X-ray emission is related to coronal magnetic activity, it is unclear what kind of structures may be the building blocks of TTS coronae and whether these coronae are created and heated by solar-like (although strongly enhanced) magnetic dynamo processes, or whether different kinds of magnetic structures and heating mechanisms are involved. Furthermore, a fundamentally different source of X-ray emission may be present in actively accreting TTS: the shocks where the accreted material crashes onto the stellar surface seem to produce soft X-ray emission in some TTS (see, e.g., Kastner et al. 2002). Hot ($\gtrsim 10-30$ MK) coronal plasma may coexist with cool ($\lesssim 1-3$ MK) plasma in accretion shocks (Schmitt et al. 2005). An important question, therefore, is whether accretion shocks are an important source of TTS X-ray emission or only relevant in a few, perhaps peculiar, objects.

## 2. Large X-ray projects on TTS

Very significant progress on these and other questions has been made in the last few years with two major observational projects that provided unprecedented X-ray data sets on TTS.

The first one is the *Chandra* Orion Ultradeep Project (COUP), a unique, 10-day long (total exposure time of 838 100 sec) observation of the Orion Nebula Cluster (ONC) with *Chandra*/ACIS (for details of the observation and data analysis see Getman et al. 2005). This is the deepest and longest X-ray observation ever made of a young stellar cluster and produced the most comprehensive dataset ever acquired on the X-ray emission of young stars. Nearly all of the 1616 detected X-ray sources could be unambiguously identified with optical or near-infrared counterparts. With a detection limit of $L_{\rm X,min} \sim 10^{27.3}$ erg/sec for lightly absorbed sources, X-ray emission from more than 97% of the $\sim$ 600 optically visible and well characterized late-type (spectral types F to M) cluster stars was detected (Preibisch et al. 2005a); as the remaining < 3% undetected stars are probably no cluster members but unrelated field stars, the COUP TTS sample is *complete*.

The other large project is the XMM-Newton Extended Survey of the Taurus Molecular Cloud (XEST), a survey of the densest stellar populations of the Taurus Molecular Cloud, in X-rays and in the near ultraviolet (for details, see Güdel et al. 2007). The principal data were extracted from 28 different XMM-Newton exposures with the EPIC cameras, covering a total of 5 square degrees, and provided X-ray data on 110 optically well characterized TTS. For several bright objects, high-resolution X-ray spectra were obtained with the Reflection Grating Spectrometers.

The main papers discussing the origin of TTS X-ray emission are Preibisch et al. (2005a) for COUP and Briggs et al. (2007) for XEST. Note that several of the results discussed below were already suspected from the data of shorter X-ray observations of different star forming regions, but were confirmed with better data quality and much higher statistical power in the COUP and XEST data sets.

## 3. Some general results

Nearly all TTS show $L_{\rm X}/L_{\rm bol} > 10^{-5}$ and are therefore much more X-ray active than the Sun ($L_{\rm X,\odot}/L_{\rm bol,\odot} \sim 10^{-6}$). There is thus no indication for the existence of an "X-ray quiet" population of stars with suppressed magnetic activity. The detection of X-ray emission from several spectroscopically-identified brown dwarfs (e.g., Preibisch et al. 2005b) clearly shows that the X-ray activity does not terminate at the stellar mass limit but extends well into the substellar regime.

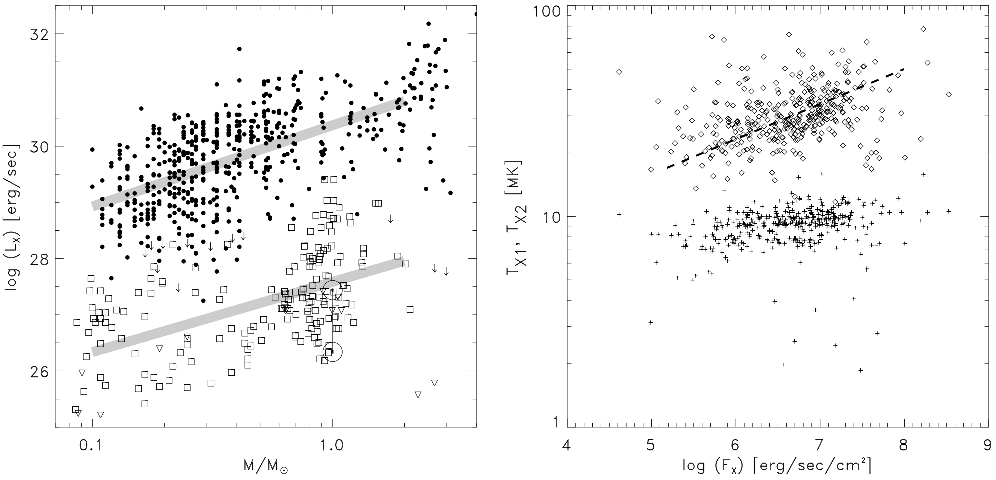

**Fig. 1. Left:** X-ray luminosity versus stellar mass for the stars in the COUP optical sample (solid dots, arrows for upper limits) and for the NEXXUS sample of nearby field stars (open squares, triangles for upper limits). The thick grey lines show linear regression fits for the low-mass ($M \leq 2\,M_\odot$) stars in these two samples. **Right:** Plasma temperatures (crosses for the cool component $T_{X1}$, diamonds for the hot component $T_{X2}$) derived in the X-ray spectral fits for the TTS in the COUP optical sample plotted versus the X-ray surface flux. The dashed line shows the relation $F_X \propto T^6$.

The X-ray luminosities of the TTS are correlated to stellar mass (Fig. 1, left) with a power-law slope similar to that found for the NEXXUS stars (Schmitt & Liefke 2004), a complete sample of nearby late-type field stars. The plasma temperatures of the COUP TTS derived in fits to the X-ray spectra with two-temperature models are shown in the right panel of Fig. 1. The temperature of the hot plasma component increases with increasing surface flux. The temperatures of the cool plasma component of most TTS are remarkable similar and around 10 MK.

The TTS generally show high-amplitude rapid variability, with typically one or two very powerful flares ($L_{\mathrm{X,peak}} \gtrsim 10^{30\ldots32}$ erg/sec) per week on each star.

## 4. X-ray emission and accretion

### 4.1. Is X-ray emission from accretion shocks important ?

According to the magnetospheric accretion scenario, accreted material crashes onto the stellar surface with velocities of up to several 100 km/sec, what should cause shocks with temperatures of up to about $\sim 10^6$ K, in which strong optical and UV excess emission and perhaps also soft X-ray emission is produced. The expected characteristics of X-ray emission from accretion shocks would be a very soft spectrum (due to the low plasma temperature in the shock), and perhaps simultaneous brightness variations at optical/UV wavelengths and in the X-ray band. Recent high-resolution X-ray spectroscopy of *some* TTS (e.g. TW Hya, XZ Tau and BP Tau, see Kastner et al. 2002; Favata et al. 2003; Schmitt et al. 2005) yielded very high electron densities ($n_e \sim 10^{13}\,\mathrm{cm}^{-3}$) in the coolest (1…5 MK), O VII and Ne IX forming plasma components, what has been interpreted as evidence for X-ray emission originating from accretion shocks (rather than coronal loops, with their typical densities of $n_e \sim 10^{9\ldots11}\,\mathrm{cm}^{-3}$).

However, neither the COUP nor the XEST results provided support for a scenario in which the X-ray emission from TTS is dominated by accretion shocks. First, the X-ray luminosities of many accreting TTS are *larger* than, or similar to, their accretion luminosities, ruling out the possibility that the bulk of the observed X-ray emission from the TTS could originate from accretion processes.

Second, the X-ray spectra of nearly all TTS show much higher plasma temperatures (typically a $\sim 10$ MK cool component and $\gtrsim 20$ MK hot component) than the $\lesssim 1 - 3$ MK expected from shocks for the typical accretion infall velocities. The vast majority of the TTS show neither significant plasma components at temperatures below 3 MK, nor indications for soft ($\lesssim 1$ keV) excesses that may hint towards emission from accretion shocks.

Third, the high-resolution spectra of TTS analyzed in the XEST project did not show any evidence for the high plasma densities as expected for accretion shocks; the derived densities are only $n_e \sim 3 \times 10^{11}\,\mathrm{cm}^{-3}$ for BP Tau and $n_e < 10^{11}\,\mathrm{cm}^{-3}$ for T Tau N and the Herbig star AB Aur (Telleschi et al. 2007). Such low densities are not compatible with standard assumptions of accretion shocks.

Fourth, from simultaneous X-ray and optical monitoring of 800 stars in the ONC, Stassun et al. (2006) found that 95% of the ONC TTS did *not* show any time-correlated X-ray - optical modulations that would be expected if surface accretion shocks were the dominant sites of X-ray production.

These results show clearly that in the vast majority of TTS the X-ray emission must be dominated by a coronal component, and not by accretion shocks. Of course, these arguments do not exclude the possibility that accretion shocks may contribute *some fraction* of the X-ray emission in TTS. It is critical to note that the CCD detectors of *Chandra* and XMM-Newton are not very sensitive to the cooler plasma expected from these accretion shocks. However, note that the scenario of X-ray emitting accretion shocks also faces problems from theoretical considerations. The existence of accretion shocks does *not* necessarily imply that one should expect *detectable* X-ray emission from these shocks: according to models of the shock structure (e.g., Calvet & Gullbring 1998), the material above the shock has typical column densities of $\gtrsim 10^{23}\,\mathrm{cm}^{-2}$ and should thus completely absorb and thermalize the soft ($\lesssim 0.5$ keV) X-rays emitted from the shock plasma within or close to the shock zone. This problem has also been highlighted by Drake (2005), who argued that for the typically estimated accretion rates in TTS ($\dot{M} \approx 10^{-7}\,M_\odot/\mathrm{yr}$), the shock is buried too deeply in the stellar atmosphere to allow the soft X-ray emission to escape and be detected; only for very low accretion rates ($\dot{M} \lesssim 10^{-9}\,M_\odot/\mathrm{yr}$) detectable soft X-ray emission can be expected.

## 4.2. The suppression of X-ray emission by accretion

The COUP data confirmed previous indications for systematic differences in the X-ray properties of accreting and non-accreting TTS. The absolute as well as the fractional X-ray luminosities of accreting TTS are systematically *lower* by a factor of $\sim 2 - 3$ than the corresponding values for non-accreting TTS. Also, X-ray activity appears to be anti-correlated with mass accretion rate. These results were very well confirmed with the XEST data and one can thus conclude that the X-ray activity of accreting TTS is somehow suppressed.

The most likely explanation for this effect are changes in the coronal magnetic field structure by the accretion process. The pressure of the accreting material may distort the large-scale stellar magnetic field (e.g. Romanova et al. 2004) and the magnetospheric transfer of material to the star can give rise to instabilities of the magnetic fields around the inner disk edge. The presence of accreting material should also lead to higher densities in (parts of) the magnetosphere; these high densities may inhibit magnetic heating of the accreting material to X-ray emitting temperatures. The accreting material will also cool the corona when it penetrates into active regions and mixes with hot plasma. If the plasma gets cooled below a few MK, its very soft X-ray emission is essentially undetectable for the CCD X-ray detectors of *Chandra* and XMM-Newton, and thus the observed X-ray luminosity of the accreting stars is lower than that of non-accretors (see also Telleschi et al. 2007).

Jardine et al. (2006) have recently modeled the X-ray emission of TTS assuming that they have isothermal, magnetically confined coronae. In stars without a circumstellar disk, these coronae extend outwards until the pressure of the hot coronal gas overcomes the magnetic field, explaining the observed increase in the X-ray emission measure with increasing stellar mass. In stars that are surrounded by a circumstellar accretion disk, the outer parts of the coronal magnetic field are stripped by the interaction with the disk. This stripping provides a good explanation for the observed lower X-ray luminosities of accreting stars.

## 5. X-ray emission from magnetic star-disk interactions?

Another possibility for a non-solar like origin of the X-ray emission from TTS may be plasma trapped in magnetic fields that connect the star with its surrounding accretion disk. The dipolar stellar magnetic field lines anchored to the inner part of the accretion disk should be twisted around because of the differential rotation between the star of the disk. This twisting should lead to reconnection events that heat the trapped plasma to very hot, X-ray emitting temperatures and produce large X-ray flares.

Favata et al. (2005) performed a detailed MHD model analysis for the ~ 30 largest flares seen in COUP data. The analysis suggests that very long magnetic structures (more than a few times the stellar radius) actually are present in *some* of the most active TTS. Such very large structures may indicate a magnetic link between these stars and their disks. However, for the majority of the analyzed flares much smaller loop lengths were found. Furthermore, the COUP and XEST results show that, in general, the X-ray luminosity is strongly linked to stellar parameters like bolometric luminosity and mass, but does not strongly depend on the presence or absence of circumstellar disks as traced by near-infrared excess emission. The bulk of the observed X-ray emission from TTS therefore originates probably from more compact coronal structures, presumably with geometries resembling solar coronal fields.

## 6. X-ray emission, rotation, and dynamos

### 6.1. X-ray activity and rotation

For main-sequence stars, the well established correlation between fractional X-ray luminosity and rotation period (e.g. Pallavicini et al. 1981; Pizzolato et al. 2003) constitutes the main argument for a solar-like dynamo mechanism as the origin of their X-ray activity. The existence of a similar relation between rotation and X-ray activity could never be convincingly established for TTS; in most studies the small number of X-ray detected TTS with known rotation periods did not allow to draw sound conclusions. A relation between rotation and X-ray activity was previously suggested for the TTS in the Taurus star forming region (Stelzer & Neuhäuser 2001); however, new data have now revealed that this is only apparent because the Taurus TTS population is biased toward fast rotators having, on average, higher mass, thus being brighter in X-rays (Briggs et al. 2007). The COUP and the XEST data have both clearly confirmed that the TTS do *not* follow the activity – rotation relation for main-sequence stars (see Fig. 2, left panel).

Theoretical studies of the solar-like $\alpha-\Omega$ dynamo show that the dynamo number is not directly related to the rotation period, but to more complicated quantities such as the radial gradient of the angular velocity and the characteristic scale length of convection at the base of the convection zone. It can be shown that the dynamo number is essentially proportional to the inverse square of the Rossby number $Ro$ (e.g. Maggio et al. 1987), which is defined as the ratio of the rotation period to the convective turnover time $\tau_c$, i.e. $Ro := P_{\rm rot}/\tau_c$. For main-sequence stars, the theoretical expectations that the stellar activity should show a tighter relationship to the Rossby number than to rotation period are well confirmed (e.g. Montesinos et al. 2001). For large Rossby numbers, activity rises strongly as $L_{\rm X}/L_{\rm bol} \propto Ro^{-2}$ until saturation at $L_{\rm X}/L_{\rm bol} \sim 10^{-3}$ is reached around $Ro \sim 0.1$, which is followed by a regime of “supersaturation” for very small Rossby numbers, $Ro \lesssim 0.02$.

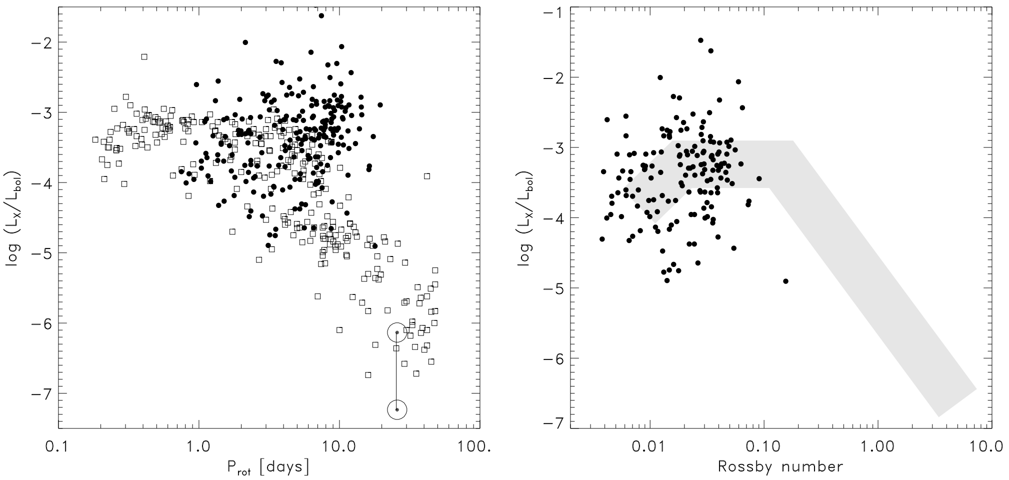

**Fig. 2. Left:** Fractional X-ray luminosity versus rotation period. This plot compares the ONC TTS (solid dots) to data for main-sequence stars from Pizzolato et al. (2003) and Messina et al. (2003) (open boxes) and the Sun. **Right:** Fractional X-ray luminosity versus Rossby number for the ONC TTS. The grey shaded area shows the relation and the width of its typical scatter found for main-sequence stars.

The convective turnover time scale is a sensitive function of the physical properties in the stellar interior. The use of semi-empirical interpolations of $\tau_c$ values as a function of, e.g., $B - V$ color, may be appropriate for main-sequence stars, but is clearly insufficient for TTS which have a very different and quickly evolving internal structure.

In the analysis of the COUP data by Preibisch et al. (2005a), convective turnover times for the ONC TTS were computed from detailed stellar evolution models with the Yale Stellar Evolution Code. The right panel in Fig. 2 shows the fractional X-ray luminosities of the ONC TTS versus the resulting Rossby numbers. The plot shows no strong relation between these two quantities. All TTS have Rossby numbers $< 0.2$ and therefore are in the saturated or super-saturated regime of the activity – Rossby number relation for main-sequence stars. However, a remarkable difference between the TTS and the main-sequence stars is apparent in the very wide dispersion of fractional X-ray luminosities at a given Rossby number among the TTS. The scatter extends over about three orders of magnitude and is in strong contrast to the tight relation found for main-sequence stars, where the scatter in $\log(L_X/L_{\rm bol})$ at a given Rossby number is only about $\pm 0.5$ dex (e.g., Pizzolato et al. 2003). This seems to suggest that additional factors, other than rotation, are important for the level of X-ray activity in TTS.

### 6.2. Implications for magnetic dynamos

The activity-rotation relation shown by main-sequence stars is usually interpreted in terms of the $\alpha$–$\Omega$-type dynamo that is thought to work in the Sun. Solar dynamo models assume that the strong differential rotation in the tachocline, a region near the bottom of the convection zone in which the rotation rate changes from being almost uniform in the radiative interior to being latitude dependent in the convection zone, generates strong toroidal magnetic fields. While most of the toroidal magnetic flux is stored and further amplified in the tachocline, instabilities expel individual flux tubes, which then rise through the convection zone, driven by magnetic buoyancy, until they emerge at the surface as active regions. The power of the dynamo (i.e. the magnetic energy created by the dynamo per unit time) is principally dependent on the radial gradient of the angular velocity in the tachocline and the characteristic scale length of convection at the base of the convection zone. Faster rotating stars have stronger velocity shear in the thin tachoclinal layer, causing the empirical relationship between X-ray luminosity and rotation rate in main-sequence stars.

Most TTS, however, are thought to be fully convective, or nearly fully convective, so the tachoclinal layer is either buried very deeply, or does not exist at all. Another kind of dynamo is thus required to explain the magnetic activity of TTS. Theoreticians have developed alternative dynamo concepts (e.g. Durney et al. 1993; Giampapa et al. 1996; Küker & Rüdiger 1999; Dobler et al. 2006) that may work in fully convective stars. A general problem with these and other models is that they disagree on the type of large-scale magnetic topologies that fully convective stars can generate, and that they usually do not make quantitative predictions that can be easily tested from observations.

Therefore, we once again consider the example of the Sun. Although the solar coronal activity is most likely dominated by the tachoclinal dynamo action, this does not prevent other dynamo processes from *also* operating. It is assumed that small scale turbulent dynamo action is taking place throughout the solar convection zone and is thought to be responsible for the small-scale intra-network fields. This means that two conceptually distinct magnetic dynamos are simultaneously operating in the contemporary Sun, although the solar coronal activity is most likely dominated by the tachoclinal dynamo action. It is therefore reasonable to assume that in the (nearly) fully convective TTS, a convective dynamo is the main source of the magnetic activity.

## 7. Implications for coronal structure

The up to $10^4$ times higher fractional X-ray luminosities of TTS clearly require that the structure of their coronae must be quite different from that of the Sun, where the X-ray emission is dominated by a moderate number of active regions with magnetic field configurations typically limited to heights of well below one stellar radius. The coronae of TTS must be either much more extended (at least several $R_*$) or consist of structures with considerably higher plasma densities than those on the Sun.

Various observational constraints are now available: Flaccomio et al. (2005) and Stassun et al. (2006) used the COUP data to search for time-correlated X-ray - optical modulations in the ONC TTS. More than 90% of the TTS did not show such time-correlated variability, what suggest a spatially rather homogenous distribution of X-ray emitting regions on the surface of the TTS. On the other hand, some TTS did show apparently periodic X-ray modulations with the same period as their rotation period (Flaccomio et al. 2005). This detection of rotational modulation in some TTS implies that the dominant X-ray emitting regions of these stars must be rather compact, distributed unevenly around the star, and do not extend significantly more than a stellar radius above the surface.

As mentioned above, the detailed MHD modeling of large flares by Favata et al. (2005) suggested that most of these flares occurred in rather compact loops ($l \lesssim R_*$) with geometries resembling solar coronal fields.

Another (tentative) clue can be derived from the remarkable similarity of the temperatures ($\sim$ 10 MK) of the cool plasma component in the COUP TTS sample. This 10 MK component seems to be a general feature of coronally active stars (e.g., Sanz-Forcada et al. 2003) and may be related to a class of very compact loops with high plasma density, presumably similar to X-ray bright points on the Sun.

## 8. Conclusions

The observed X-ray properties of TTS strongly suggest that the bulk of their X-ray emission has its origin in coronal magnetic activity. The surface of the TTS is probably covered by a large number of compact and very dense magnetic structures, which confine the X-ray emitting plasma. Magnetic interaction between these regions may be the driving source of the frequent and powerful X-ray flares.

In *some* TTS, very extended magnetic structure with lengths of $> 10 \times R_*$, which presumably connect the star to the circumstellar disk, seem to be involved.

The TTS do not follow the activity-rotation relation seen in late-type main-sequence stars and the action of a solar-like $\alpha-\Omega$-type dynamo seems to be excluded by their (nearly) fully convective stellar structure. The ultimate origin of the X-ray activity of the TTS may be a turbulent dynamo working in the stellar convection zone.

Accretion shocks at the stellar surface can not be responsible for the bulk of the observed X-ray emission in the vast majority of TTS. Despite observational hints towards accretion shock related X-ray emission in some TTS, this emission mechanism seems important (in comparison to coronal emission) only in a few exceptional objects.

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