*14th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*
*ASP Conference Series, Vol. x, 2007*
*Ed. Gerard van Belle*

# Highlights from the XMM-Newton Extended Survey of the Taurus Molecular Cloud (XEST)

Manuel Güdel,[1] Kaspar Arzner,[1] Marc Audard,[2,3] Jerôme Bouvier,[4] Kevin Briggs,[1] Catherine Dougados,[4] Eric Feigelson,[5] Elena Franciosini,[6] Adrian Glauser,[1] Nicolas Grosso,[4] Sylvain Guieu,[4] François Ménard,[4] Giusi Micela,[6] Jean-Louis Monin,[4] Thierry Montmerle,[4] Deborah Padgett,[7] Francesco Palla,[8] Ignazio Pillitteri,[6,9] Thomas Preibisch,[10] Luisa Rebull,[7] Luigi Scelsi,[6,9] Bruno Silva,[11] Stephen Skinner,[12] Beate Stelzer,[6] and Alessandra Telleschi[1]

**Abstract.** The *XMM-Newton Extended Survey of the Taurus Molecular Cloud* (XEST) is a large program designed to systematically investigate the X-ray properties of young stellar/substellar objects in the Taurus star forming region. This paper summarizes selected key findings from XEST.

## 1. Introduction

The *XMM-Newton Extended Survey of the Taurus Molecular Cloud* (XEST) is a large program to survey the densest stellar populations of the nearest large star-forming region, the Taurus Molecular Cloud (TMC), in X-rays and in the near ultraviolet (or the U band). The project is described in detail in Güdel et al. (2007a). The principal data were extracted from 28 different *XMM-Newton* (Jansen et al. 2001) exposures with the EPIC cameras (Turner et al. 2001; Strüder et al. 2001), covering a total of $\approx$5 sq. degrees, while the Optical Monitor

[1]Paul Scherrer Institut, Würenlingen and Villigen, 5232 Villigen PSI, Switzerland

[2]Columbia Astrophysics Laboratory, 550 West 120th Street, New York, NY 10027

[3]ISDC & Geneva Observatory, University of Geneva, Ch. d'Ecogia 16, 1290 Versoix, Switzerland

[4]Laboratoire d'Astrophysique de Grenoble, Université J. Fourier, 38041 Grenoble Cedex, Fr

[5]Department of Astronomy & Astrophysics, Penn State University, 525 Davey Lab, University Park, PA 16802, USA

[6]INAF - Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, 90134 Palermo, It

[7]Spitzer Science Center, California Institute of Technology, Pasadena, CA, USA

[8]INAF - Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi, 5, 50125 Firenze, It

[9]Università degli Studi di Palermo, Piazza del Parlamento 1, 90134 Palermo, It

[10]Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany

[11]Universidade do Porto, 4050-345, Porto, Pt

[12]CASA, UCB 389, University of Colorado, Boulder, CO 80309-0389, USA

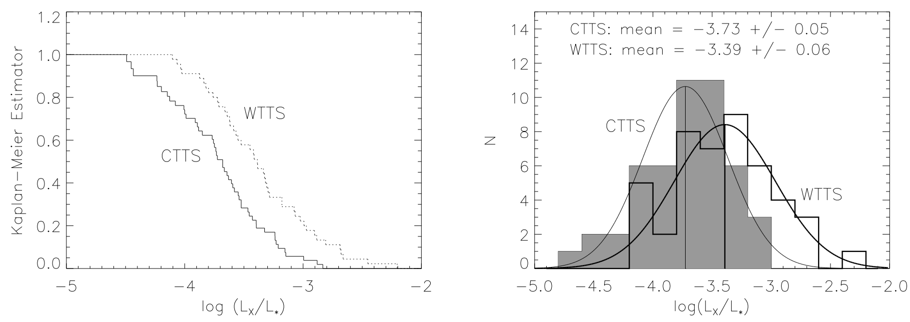



Figure 1. Left: Kaplan-Meier estimator (including a few upper limits) for $L_{\rm X}/L_{\rm bol}$ for CTTS (solid) and WTTS (dotted). The two distributions are different at the 99.97–99.99% level. Right: $L_{\rm X}/L_{\rm bol}$ distributions for WTTS (white) and CTTS (gray). (After Telleschi et al. 2007a.)

(OM, Mason et al. 2001) observed in a near-ultraviolet band or in the U band. We observed several bright objects with the Reflection Grating Spectrometers (RGS, den Herder et al. 2001). A few additional X-ray detections were added from observations extracted from the *Chandra* data archive.

## 2. Population Studies

The low-mass TMC population is clearly not yet completely known. Scelsi et al. (2007) used information from 2MASS and XEST (near-infrared color properties, $L_{\rm X}$, X-ray light curves and spectra) to identify a sample of 12 likely and another $\approx 60$ possible new members of the TMC in the surveyed area. Follow-up observations are needed to characterize these objects.

A growing number of substellar objects have recently been detected in the TMC (e.g., Guieu et al. 2006). XEST observed 17 TMC brown dwarfs and detected X-rays from 9 of them (Grosso et al. 2007a). While their overall X-ray characteristics compare well with those of slightly more massive T Tauri stars (TTS), a trend toward less efficient X-ray emission ($L_{\rm X}/L_{\rm bol} \approx 10^{-4}$) compared to late-type stars is found; this may be related to the progressively lower ionization degree toward cooler objects. On the other hand, X-ray emitting BDs are found among accretors and non-accretors, with no significant difference.

Apart from the common X-ray saturation law for TTS, X-rays seem to be correlated with stellar mass, $L_{\rm X} \propto M^{1.7\pm0.2}$ (Telleschi et al. 2007a), as previously recognized in other star-forming regions (e.g., Preibisch et al. 2005). However, the XEST project showed that this relation follows directly from the saturation law combined with the approximate mass vs. bolometric-luminosity relation for a low-mass pre-main sequence stellar population with ages of 1–5 Myr.

A remarkable relation between rotation and X-ray activity was previously suggested for TMC, in contrast to populations in other star-forming regions (Stelzer & Neuhäuser 2001). However, this relation appears to result from the bias that the fast rotators in the TMC have typically higher mass than slow rotators and are therefore brighter in X-rays (Briggs et al. 2007).

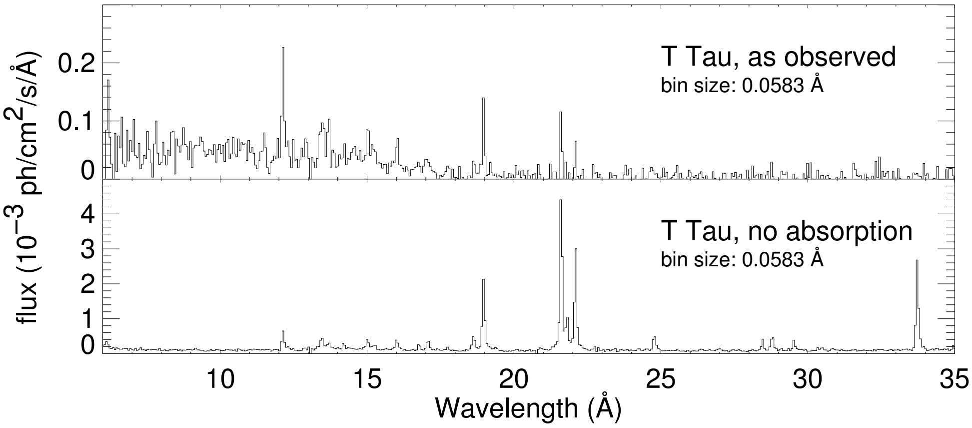



Figure 2. RGS X-ray spectrum of T Tau. Top: as observed; bottom: modeled after removal of absorption. Note high O VII $\lambda$21.6/O VIII $\lambda$19.0 Ly$\alpha$ flux ratio, and low-density indications in the O VII triplet (Güdel et al. 2007b).

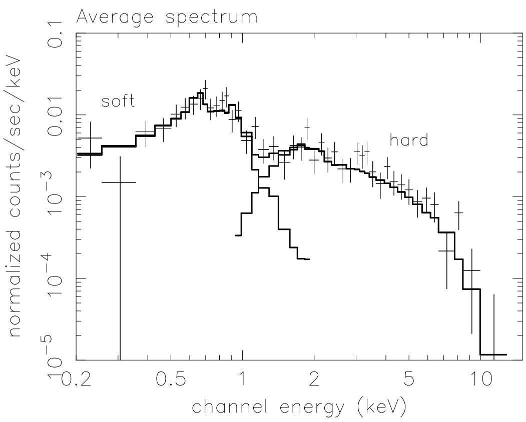
## 3. X-rays and Accretion: A "Soft Excess"

The XEST stellar sample shows a clear dichotomy between accretors and non-accretors in that both $L_X$ and $L_X/L_{bol}$ are suppressed by a factor of $\approx 2$ in the accretors (Figure 1, Telleschi et al. 2007a) while the distributions of $L_{bol}$ are similar for the two samples. Clearly, accretion somehow suppresses X-ray emission (see also Preibisch et al. 2005 for the Orion sample).

Previous high-resolution X-ray spectroscopy of a few classical TTS (CTTS), in particular TW Hya, has indicated very high electron densities ($n_e \approx 10^{13}$ cm$^{-3}$) in the coolest (1-5 MK), O VII and Ne IX forming, plasma (e.g., Kastner et al. 2002; Stelzer & Schmitt 2004). The XEST sample confirms intermediately high densities ($n_e \approx 3 \times 10^{11}$ cm$^{-3}$) for one accretor, BP Tau (Telleschi et al. 2007b), but finds low densities ($< 10^{11}$ cm$^{-3}$) for two others: T Tau N (Güdel et al. 2007b, Figure 2) and the Herbig star AB Aur (Telleschi et al. 2007c). These low densities are not compatible with standard assumptions of shocks formed by nearly free-falling accretion columns.

On the other hand, Telleschi et al. (2007b) report a systematic enhancement of the O VII/O VIII Ly$\alpha$ flux ratio in CTTS compared with those of weak-lined TTS (WTTS), in which the O VII triplet remains undetected even for low absorption. This trend points to a *soft excess in accreting stars*, i.e., the presence of a large amount of cool ($< 2$ MK) plasma. In the spectrum of T Tau N, the O VII resonance line would be the strongest line in the 1–35 Å range if no absorption were present (Güdel et al. 2007b, Figure 2).

Given that X-rays from accretion shocks are unlikely to be important in cases such as T Tau N, Telleschi et al. (2007b) and Güdel et al. (2007b) proposed that the accreting material cools the corona by penetrating into active regions, mixing with hot plasma and moderately enhancing the density, thus increasing the coronal radiative losses; this results in an excess at the cool end of the emission measure distribution. Because CCD spectroscopy does not access the softest X-ray components, the X-ray emission appears to be suppressed although high-resolution spectroscopy recovers the cooled material. While pend-



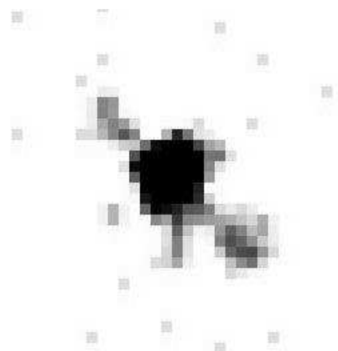


Figure 3. Left: EPIC spectrum of DG Tau A (Güdel et al. 2007c). Right: Chandra image of DG Tau A with jets (NE-SW; pixel size is 0.5″; Güdel et al., in preparation).

ing confirmation, this model can explain both the soft excess and the suppressed "normal" coronal emission in CTTS in one fell swoop; high densities would result from strong mixing between accreting and coronal material.

Accretion signatures have also been recorded by the OM. Audard et al. (2007) found a U band excess in the de-reddened TMC CTTS sample (compared to WTTS). The U band excess is commonly attributed to accretion hot spots. No correlated variability was, however, found in U-band and X-ray light curves, suggesting that the X-rays detected by the EPIC cameras are predominantly coronal. Specifically, Grosso et al. (2007b) reported a slow increase of the U-band flux in a brown dwarf by about one magnitude, without accompanying X-ray signal. The most likely interpretation is in terms of an "accretion event" in which the mass accretion rate temporarily increased by a factor of a few.

## 4. X-Rays from Outflows: Two-Absorber X-Ray Spectra

For extremely strong accretors in TMC, a new type of X-ray spectral phenomenology was described by Güdel et al. (2007c), first discovered for DG Tau A (Güdel et al. 2005). Several TMC CTTS reveal X-ray spectra that are composed of two emission components subject to entirely different photoelectric absorption (Figure 3). The intense soft component, subject to very low absorption ($N_{\rm H} \approx 10^{21}$ cm$^{-2}$), indicates temperatures of only 2–5 MK. A much harder but strongly absorbed component ($N_{\rm H}$ of several times $10^{22}$ cm$^{-2}$), in contrast, suggests extremely hot (several tens of MK) plasma. Flares in the X-ray light curves show up exclusively in the hard component while the soft component remains steady. Evidently, these "two-absorber" X-ray spectra require that *two physically unrelated X-ray sources are present around these objects.*

A tentative interpretation is the following (Güdel et al. 2005, 2007c): The flaring in the hard component on timescales of hours suggests ordinary coronal active regions. These regions are therefore likely to be of modest size, well connected to the surface active regions. The excess absorption is due to cool gas that streams in from the disk along the magnetic field lines, enshrouding the magnetosphere with absorbing material. This increases the photoelectric absorption of X-rays but does not increase the optical extinction because the gas streams are very likely to be depleted of dust, the latter being evaporated farther away from the star. This absorption component thus provides indirect evidence for both the presence of accreting gas streams and for dust destruction.

The low absorption of the cool X-ray component makes an interpretation in terms of accretion shocks or accretion cooling of active regions problematic and points to a location outside the magnetosphere. An obvious location is in shocks forming near the base or the collimation region of the jet (e.g., Bally, Feigelson, & Reipurth 2003). A *Chandra* high-resolution image of DG Tau A (Figure 3; Güdel et al. 2007, in prep.) shows X-rays both from the jet and the counter-jet, with a spectrum that is (up to normalization) consistent with the soft spectral component of the entire system. *Chandra* seems to resolve the most distant jet shocks while more may be located within the unresolved stellar image.

**Acknowledgments.** We thank the International Space Science Institute (ISSI) in Bern for financial support of the project. This research is based on observations obtained with *XMM-Newton*, an ESA science mission with instruments and contributions directly funded by ESA member states and the USA (NASA). The PSI group has been supported by the Swiss National Science Foundation (NSF grants 20-66875.01 and 20-109255/1). MA acknowledges support by NASA (grant NNG05GF92G) and the Swiss NSF (grant PP002–110504). The Grenoble group thanks PNPS of CNRS/INSU, France, for partial support. The Palermo group acknowledges support from contract ASI-INAF I/023/05/0.

**References**

Audard, M., Briggs, K. R., Grosso, N., et al. 2007, A&A, in press
Bally, J., Feigelson, E., & Reipurth, B. 2003, ApJ, 584, 843
Briggs, K. R., Güdel, M., Telleschi, A., et al. 2007, A&A, in press
den Herder, J. W., Brinkman, A. C., Kahn, S. M., et al. 2001, A&A, 365, L7
Grosso, N., Briggs, K. R., Güdel, M., et al. 2007a, A&A, in press
Grosso, N., Audard, M., Bouvier, J., et al. 2007b, A&A, in press
Güdel, M., Skinner, S. L., Briggs, K. R., et al. 2005, ApJ, 626, L53
Güdel, M., Briggs, K. R, Arzner, K., et al. 2007a, A&A, in press
Güdel, M., Skinner, S. L., Mel'nikov, S. Y., et al. 2007b, A&A, in press
Güdel, M., Telleschi, A., Audard, M., et al. 2007c, A&A, in press
Guieu, S., Dougados, C., Monin, J.-L., Magnier, E., & Martín, E. L. 2006, A&A, 446, 485
Jansen, F., Lumb, D., Altieri, B., et al. 2001, A&A, 365, L1
Kastner, J. H., Huenemoerder, D. P., Schulz, N. S., Canizares, C. R., & Weintraub, D. A. 2002, ApJ, 567, 434
Mason, K. O., Breeveld, A., Much, R., et al. 2001, A&A, 365, L36
Preibisch, T., Kim, Y.-C., Favata, F., et al. 2005, ApJS, 160, 401
Scelsi, L., Maggio, A., Micela, G., et al. 2007, A&A, in press
Stelzer, B., & Neuhäuser, R. 2001, A&A, 377, 538
Stelzer, B., & Schmitt, J. H. M. M. 2004, A&A, 418, 687
Strüder, L., Briel, U., Dennerl, K., et al. 2001, A&A, 365, L18
Telleschi, A., Güdel, M., Briggs, K. R., Audard, M., & Palla, F. 2007a, A&A, in press
Telleschi, A., Güdel, M., Briggs, K. R., Audard, M., & Scelsi, L. 2007b, A&A, in press
Telleschi, A., Güdel, M., Briggs, K. R., et al. 2007c, A&A, in press
Turner, M. J. L., Abbey, A., Arnaud, M., et al. 2001, A&A, 365, L27