EXPLORING THE EVOLUTION OF YOUNG STELLAR CORONAE IN TAURUS

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ABSTRACT

XMM-Newton's X-ray Emission Survey of Taurus (XEST) is an exceptionally large study of the X-ray emission from low-mass stars in the early stages of stellar life. In these early stages, X-ray emission is a key agent for ionizing the circumstellar environment and determining the importance of magnetic fields therein. We probe the origin and evolution of X-ray emission from young stars in the Taurus Molecular Cloud by investigating the dependence of the X-ray activity level on accretion rate and rotation period, finding that accreting young stars have typically lower X-ray activity levels with a rotation dependence suggestive of a solar-like dynamo.

Key words: X-rays: stars; Stars: pre-main sequence.

1. XEST

The Taurus Molecular Cloud (TMC) is one of the closest (140 pc) star-forming regions (SFRs). Its distributed nature, stretching across 10 deg of sky, its strongly peaked initial mass function (IMF) at 0.8 $M_\odot$, and absence of ionizing high-mass stars mark it out from densely clustered SFRs such as the Orion Nebula Cluster (ONC), whose IMF peaks at 0.2 $M_\odot$.

In our X-ray Emission Survey of Taurus (XEST), XMM-Newton has observed 19 of the denser fields of the TMC for 30 ks each, supplemented by 7 archival observations of similar or longer exposure. An overview of the project is given by Güdel et al. 2006, while Audard et al. 2006 and Grosso et al. 2006 concentrate on specific aspects. Here, we focus on a comparison of the X-ray characteristics of young stars that show signatures of active accretion (Classical T Tauri Stars or CTTS) with those that do not (Weak-line T Tauri Stars or WTTS). It is presumed that all WTTS have passed through a phase as a CTTS although there is no fixed timescale for this process: 10 Myr old CTTS exist as well as 1 Myr old WTTS.

XEST extends previous X-ray surveys of the TMC as the greater sensitivity, and energy range (0.1–15 keV) and resolution of XMM-Newton's EPIC cameras enable detection of fainter sources, and more accurate spectral modelling and X-ray luminosity determination. With a characteristic detection limit of $\approx 1 \times 10^{28}$ erg s^{-}1 we detected 60 of 66 single or unresolved multiple CTTS and 39 of 42 WTTS in the survey. The CTTS and WTTS samples have similar mass distributions. 13 CTTS and 10 WTTS have known rotation periods, P and 16 CTTS and 8 WTTS have projected rotational velocities from which P can be estimated on a statistical basis. CTTS ($P \sim 8$ d) are typically slower rotating than WTTS ($P \sim 4$ d).

2. RESULTS

The dominant origin of X-ray emission in young stars in the TMC appears to be a magnetic corona. With the exception of four CTTS with outstandingly high outflow rates (see Güdel et al. 2006 and Audard et al. 2006), the observed EPIC X-ray spectra of all CTTS and WTTS are well-described by a model based on the coronae of solar analogues (see Telleschi et al. 2006). The observed plasma temperatures of > 10 MK are too hot to originate in shocks in accretion columns or jets. There are no significant differences in the coronal temperature distributions of CTTS and WTTS, and in both samples, $L_{\rm X}$ scales strongly with a star's bolometric luminosity, $L_{\rm bol}$, and its mass, while the activity level, $L_{\rm X}/L_{\rm bol}$, shows no correlation with either (Güdel et al. 2006). However, the mean activity level of WTTS ($\log L_{\rm X}/L_{\rm bol} = -3.33 \pm 0.07$) is significantly higher than that of CTTS ($\log L_{\rm X}/L_{\rm bol} = -3.64 \pm 0.07$), confirming the result of previous X-ray studies of the TMC (Stelzer & Neuhäuser 2001; SN01), and in good agreement with results from the Chandra Orion Ultradeep Project based on the much larger sample of young stars in the ONC (Preibisch et al. 2005; P05). Yet we find no correlation of $L_{\rm X}/L_{\rm bol}$ with mass accretion rate that one might expect if accretion had a direct effect on the corona (Güdel et al. 2006).

The dependence of $L_{\rm X}$ on rotation period, P, in mature low-mass stars like the Sun is taken to be strong evidence that coronae are powered by a magnetic dynamo, located at the interface of the internal radiative zone and convective envelope. On the fastest rotators, $\log L_{\rm X}/L_{\rm bol}$ saturates at ≈ -3. Stars with longer internal convective turnover times, τ, saturate already at longer P, and even fully-convective low-mass stars, which require a different dynamo mechanism, show this behaviour.

Slower rotators in TMC have on average lower $L_{\rm X}/L_{\rm bol}$ than fast rotators, a tendency which is clear among CTTS, but not WTTS (Fig. 1). If we assume a solar-like $L_{\rm X}/L_{\rm bol}$ vs P relation and fit the period at which saturation occurs, we find a value around 6 d for CTTS but no value below 12 d (Fig. 2) for the WTTS (i.e. all are saturated). A correlation of X-ray activity with rotation has been seen in earlier studies of the TMC (SN01) but not in other SFRs. Young stars in the ONC (P05) concentrate around $P \approx 6$–11 d, $\log L_{\rm X}/L_{\rm bol} \approx -3.4$ to -2.7, an area sparsely populated in the TMC.

3. DISCUSSION

Stellar evolutionary models excluding accretion indicate young stars should be fully convective. τ should be long enough that X-ray activity levels are saturated over the range of P in Fig. 1 (P05). However, Wuchterl & Tscharnuter (2003) show that during the accretion (CTTS) phase young stars of 0.5–2 $M_\odot$ (but not lower mass) have internal radiative zones, like the Sun. Then a solar-like dynamo can operate, τ is shorter, and CTTS may have unsaturated, lower activity levels at $P > 6$ d, while WTTS have saturated, higher activity levels. In this case, the activity level may be a complex function of rotation period, age, mass and accretion rate. Possibly age and mass distributions in the TMC allow the display of an activity–rotation relation while those in the ONC do not. Very careful study is likely necessary to unravel the controlling influences on X-ray emission in young stars.

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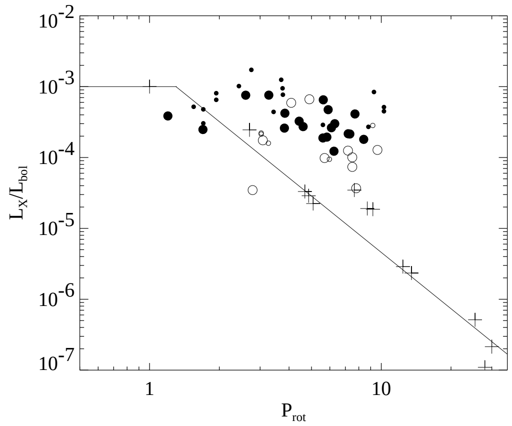

Figure 1. Plot of activity level vs rotation period for CTTS (larger symbols) and WTTS (smaller). Open circles show sources with $<$ 400 counts. The line shows the relation for solar analogues (crosses; Telleschi et al. 2005).

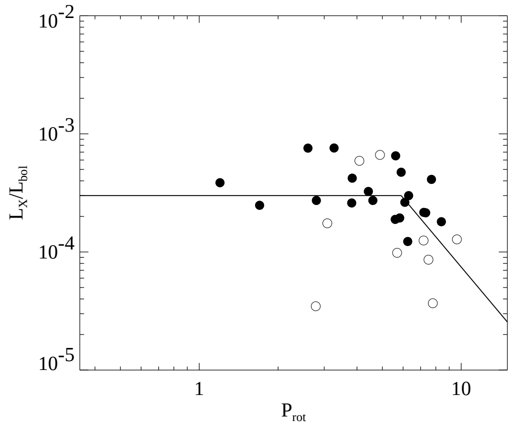

Figure 2. As Fig. 1 for CTTS only. The period and level of saturation of a solar-like relation are fitted.

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