X-RAY EMISSION FROM STAR FORMING REGIONS

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A quick tour of PMS stars

<table>
<thead>
<tr>
<th>PROPERTIES</th>
<th>Infalling Protostar</th>
<th>Evolved Protostar</th>
<th>Classical T Tauri Star</th>
<th>Weak-lined T Tauri Star</th>
<th>Main Sequence Star</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sketch</strong></td>
<td><img src="image" alt="Sketch" /></td>
<td><img src="image" alt="Sketch" /></td>
<td><img src="image" alt="Sketch" /></td>
<td><img src="image" alt="Sketch" /></td>
<td><img src="image" alt="Sketch" /></td>
</tr>
<tr>
<td><strong>Age (Years)</strong></td>
<td>$10^4$</td>
<td>$10^5$</td>
<td>$10^6 - 10^7$</td>
<td>$10^6 - 10^7$</td>
<td>$&gt; 10^7$</td>
</tr>
<tr>
<td><strong>mm/Infrared Class</strong></td>
<td>Class 0</td>
<td>Class I</td>
<td>Class II</td>
<td>Class III</td>
<td>(Class III)</td>
</tr>
<tr>
<td><strong>Disk</strong></td>
<td>Yes</td>
<td>Thick</td>
<td>Thick</td>
<td>Thin or Non-existent</td>
<td>Possible Planetary System</td>
</tr>
<tr>
<td><strong>X-ray</strong></td>
<td>?</td>
<td>Yes</td>
<td>Strong</td>
<td>Strong</td>
<td>Weak</td>
</tr>
<tr>
<td><strong>Thermal Radio</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>Non-Thermal Radio</strong></td>
<td>No</td>
<td>Yes</td>
<td>No ?</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Adapted from Feigelson & Montmerle, ARA&A, 1999
1. Diffuse X-ray emission from star forming clouds

2. X-ray emission from low mass PMS stars
   - Coronae (Results from COUP, XEST, DROXO)
   - Accretion
   - Jets

3. Effects of X-rays on circumstellar disks
Found in high mass SFR:

Orion (Guedel et al. 2008),
NGC2024 (Ezoe et al. 2006),
M17 (Townsley et al. 2003),
Rosette (Wang et al. 2009),
Westerlund 1 (Muno et al. 2006),
Carina Nebula (Ezoe et al. 2009),
RCW38 (Wolk et al. 2002, 2006),
NGC6334 (Ezoe et al. 2006),
30 Dor (LMC; Townsley et al. 2006)

\[ T \sim 1-10 \text{ MK} \]
\[ L_X = 3.4 \times 10^{33} \text{ ergs/s} \]

Wind-wind, wind-cloud collision
Orion Nebula Cluster
Guedel et al. (2008)

\[ T \sim 2 \text{MK} \]
\[ L_X = 5.5 \times 10^{31} \text{ergs/s} \]
1. Diffuse X-ray emission from star forming clouds

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   - Coronae (Results from COUP, XEST, DROXO)
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Known T Tauri stars bright X-ray sources
$L_X \sim 10^{30} \text{ ergs s}^{-1}$

A number of other other X-ray sources also detected: Weak line T-Tauri Stars (WTTS)

Gahm (1980); Feigelson and Decampli (1981); Feigelson and Kriss (1981); Walter and Kuhi (1981); Feigelson and Kriss (1983); Montmerle et al. (1983); Mundt et al. (1983); Walter and Kuhi (1984); Herbig, Vrba and Rydgren (1986); Walter (1986); Walter et al. (1987); Feigelson et al. (1987); Walter et al. (1988); Feigelson and Kriss (1989); Damiani et al. (1990); Walter (1992); Walter et al. (1994); Walter et al. (1997).
ρ Ophiuchi: an “X-ray Christmas tree”
Montmerle et al. 1983 (Einstein IPC data)
850 ks Chandra on Orion Nebula Cluster (~ 1Myr)

PI: E. Feigelson

13 papers in ApJS Special Issue 160 and several others

1616 X-ray sources of which >1300 cloud members
XMM-Newton Extended Survey in Taurus (XEST)

19 x 30 ks XMM-Newton in Taurus Molecular cloud (+ 9 XMM-Newton fields in Taurus from archive)

PI: M. Guedel

15 papers in A&A Special Issue 468

126 cloud members detected, 33 cloud members undetected
Deep Rho Ophiuchi XMM-Newton Observation (DROXO)

500 ks XMM-Newton on ρ Oph core F

PI: S. Sciortino

2 paper published, several others in prep.

111 X-ray sources

~ 0.5 Myr PMS stars
Comparison with previous results

Stars with measured photometric rotation periods; the open black symbols have periods derived from and triangles show, respectively, non-accreting and accreting T Tauri stars in Taurus-Auriga in the present study. The filled black symbols show studied by Pizzolato et al. (2003); grey open squares show T Tauri stars in the Orion Nebula Cluster studied by Preibisch et al. (2005); black circles

fig. 7.

A larger scatter in in the ONC and are mostly fast-rotating. The ONC stars have lower-mass T Tauri stars, whose rotational properties are poorly resolved by analogy with solar-like main-sequence stars. Accretion cannot be the cause of lower activity should show saturated emission with rotation period. Because the accretors have much more overlap in this period that we have found for the combined sample of accreting and non-accreting stars in non-accreting T Tauri stars, so such stars are potentially very interesting for investigating the diurnal oscillations in X-ray emission.

The T Tauri stars in Taurus-Auriga are concentrated to higher Rossby numbers than those in the ONC. This is mainly due to the dominance of younger T Tauri stars experience greater X-ray variability, or it could be due to absorbing column density, which is higher for Taurus-Auriga than for the ONC (Preibisch et al. 2005). This difference in absorbing column density is consistent with the observed differences in X-ray luminosity between the two clusters.

We have made a careful reexamination of the data used by Stelzer & Neuhäuser (2001) to try to improve the determination of the Rossby number. The grey leftward-pointing arrows represent periods derived from PSPC had, in principle, the spectroscopic capability to measure circumstellar material in the line of sight to the star. The depopulation of accreting stars due to abiding on hardness ratio. Our calculations using the PSPC on-detector conversion factor that aimed to account for absorption through a dependence on the energy bandpass. The conversion factor that accounted for absorption only due to absorption was primarily due to absorption in the soft energy bandpass of 0.1–2.4 keV and low sensitivity, especially at harder energies, combined with modest exposure times, which allowed for approximately 2 dex of sensitivity.

The ratio of X-ray and stellar luminosities plotted as a function of Rossby number. Grey filled circles show late-type main-sequence stars with rotation period. All PMS stars in the saturated regime, but much larger scatter with respect to MS stars:

A) Variability
B) Unresolved binaries → make up for <0.5 dex
C) Accretion?
Accretion disks affect (depress) activity? 

Preibisch et al. (2005)
X-ray luminosities of Class I objects (ONC / COUP)

Class 0-Ia
Class 0-Ib
Class II
Class III

0.9–1.2 M☉
Possible explanation for lower $L_x$ of accretors:

- Higher density $\rightarrow$ less efficient heating
- X-ray emission obscured by accretion streams

Gregory et al. (2007)
Fig. 1.— X-ray heating-induced photoevaporation rate, $\dot{M}$, from a 2D protoplanetary disk model expressed as a function of the model coronal X-ray luminosity of the central star, $L_X$, computed using the Mocassin program (see text and Ercolano et al. 2008a for details).

\[
\log L_X [\text{erg s}^{-1}] = \begin{cases} 
29.3 \\
29.9 \\
30.5 \\
31.0 \\
31.6 
\end{cases}
\]

Fig. 2.— The photoevaporation rate per unit radius, $d\Sigma / dt$, as a function of radial distance from the central star for different stellar X-ray luminosities, $L_X$. The evaporation rate peaks in the region 20 AU and at high values of $L_X$ can compete with the inward viscous flow, starving the inner disk of the replenishing gas from the outer disk that contains the bulk ($\sim 90\%$) of the total disk gas mass.

Drake et al. (2009)
Flare energy distribution
Nanoflare heating?

\[
\frac{dN}{dE} \sim E^{-\alpha}
\]

If \( \alpha > 2 \) the integral diverges for \( E_{\text{min}} \to 0 \) infinite amount of energy in nano-flares

Aschwanden et al. (2000)
Flare number energy distribution
COUP solar-analogs + XEST stars

\[ \alpha = 1.9 \pm 0.3 \]

\[ \alpha = 2.4 \pm 0.5 \]

Stelzer et al. (2007)
Flare energy distributions in all Pre-MS samples support nano-flare heating, but completeness limits for energy are high.

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Log $E_{\text{cut}}$</th>
<th>$\alpha$</th>
<th>$F_{\text{fl}}$ with $E &gt; E_{\text{cut}}$</th>
<th>Exp.T [ks]</th>
<th>$N_{\text{stars}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>COUP solar analogs</td>
<td>35.3</td>
<td>1.9 +/- 0.3</td>
<td>1 / 1150 ks</td>
<td>850</td>
<td>28</td>
</tr>
<tr>
<td>COUP very low-mass</td>
<td>-</td>
<td>2.2 +/- 0.2</td>
<td>-</td>
<td>850</td>
<td>165</td>
</tr>
<tr>
<td>COUP all</td>
<td>35.6</td>
<td>2.05 +/- 0.15</td>
<td>1 / 5542 ks</td>
<td>850</td>
<td></td>
</tr>
<tr>
<td>XEST all</td>
<td>34.9</td>
<td>2.4 +/- 0.5</td>
<td>1 / 770 ks</td>
<td>30</td>
<td>22</td>
</tr>
<tr>
<td>CygOB2 low mass</td>
<td>35.1</td>
<td>2.1 +/- 0.1</td>
<td>1 / 1320 ks</td>
<td>100</td>
<td>1003</td>
</tr>
</tbody>
</table>

Wolk et al. (2005), Caramazza et al. (2007), Stelzer et al. (2007), Albacete Colombo et al. (2007)
Physical modelling of 32 bright flares

Favata et al. (2005)

\[ L = \frac{\tau_{lc} \sqrt{T_{pk}}}{3.7 \times 10^{-4} F(\zeta)} \cdot \]

Reale et al. (1997)

A significant number of flares (~10) imply loops longer than 5 R_*
Is this common? Are all X-rays emitted in such loops?
Rotational modulation is detected in >10% of the sample. Amplitudes: 20-70%

X-ray emitting structures must be compact (< R*)
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   - Jets

3. Effects of X-rays on circumstellar disks
X-rays from protostellar and pre-MS jets

DG Tau - Guedel et al. (2007)

Guedel et al. (2008)
Only a handful of pre-MS jet shocks have been detected in X-rays.

<table>
<thead>
<tr>
<th>Object</th>
<th>$L_X$ [10^{39} \text{ erg s}^{-1}]</th>
<th>$kT$ [keV]</th>
<th>$N_{\text{H}}$ [10^{22} \text{ cm}^{-2}]</th>
<th>$v_{\text{sh}}$ [km s$^{-1}$]</th>
<th>$D$ [pc]</th>
<th>$L_{\text{bol}}/L_\odot$</th>
<th>$L_X/L_{\text{bol}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH 2</td>
<td>5.2</td>
<td>0.23</td>
<td>$\leq 0.09$</td>
<td>230</td>
<td>480</td>
<td>81$^a$</td>
<td>$1.7 \times 10^{-6}$</td>
</tr>
<tr>
<td>HH 154</td>
<td>3.0</td>
<td>0.34</td>
<td>1.40</td>
<td>500</td>
<td>140</td>
<td>40$^b$</td>
<td>$9.7 \times 10^{-7}$</td>
</tr>
<tr>
<td>HH 80/81</td>
<td>450</td>
<td>0.13</td>
<td>0.44</td>
<td>700</td>
<td>1700</td>
<td>$2 \times 10^4c$</td>
<td>$1.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>HH 168</td>
<td>1.1</td>
<td>0.5</td>
<td>0.40</td>
<td>500</td>
<td>730</td>
<td>2.5$\times 10^4c$</td>
<td>$3.6 \times 10^{-7}$</td>
</tr>
<tr>
<td>HH 210</td>
<td>10</td>
<td>0.07–0.33</td>
<td>0.80</td>
<td>130</td>
<td>450</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Bonito et al. (2007)

Calculations for jets with different Mach number (plotting symbols) and different medium/jet density contrast (size of symbols).
1. Diffuse X-ray emission from star forming clouds
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X-rays and circumstellar disk

- Stellar X-rays heat and ionize circumstellar disks (e.g., Igea & Glassgold 1999, Glassgold et al. 2004)
- Significant effects on disk structure/evolution and planet formation e.g.: viscosity, photoevaporation (>EUV)

Glassgold et al. (2007), Mejierink et al. (2008), Gorti & Hollenback (2008), Ercolano et al. (2009)
**Fe 6.4 keV - COUP**

Tsujimoto et al. (2005)

<table>
<thead>
<tr>
<th>COUP Sequence Number</th>
<th>$k_B T_{d,r}$ (keV)</th>
<th>$L_{X_{d,r}}$ (10^{34} \text{ ergs s}^{-1})</th>
<th>$L_{X_{\text{peak}}}$ (10^{38} \text{ ergs s}^{-1})</th>
<th>$N_{K_{\alpha}}$ (10^{-7} \text{ cm}^{-2} \text{ s}^{-1})</th>
<th>EW_{K_{\alpha}} (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>331</td>
<td>4.6 (4.3–5.6)</td>
<td>3.4 (2.7–3.9)</td>
<td>17</td>
<td>2.6 (0.1–4.6)</td>
<td>126</td>
</tr>
<tr>
<td>561</td>
<td>2.8 (2.6–2.9)</td>
<td>5.6 (5.8–6.1)</td>
<td>4.4</td>
<td>3.6 (1.1–7.3)</td>
<td>130</td>
</tr>
<tr>
<td>621</td>
<td>3.2 (2.9–3.4)</td>
<td>4.1 (3.4–4.8)</td>
<td>1.6</td>
<td>2.5 (0.5–3.9)</td>
<td>111</td>
</tr>
<tr>
<td>647</td>
<td>5.7 (4.7–8.1)</td>
<td>3.3 (2.9–4.1)</td>
<td>5.7</td>
<td>4.1 (1.9–6.2)</td>
<td>135</td>
</tr>
<tr>
<td>649</td>
<td>3.0 (2.6–3.1)</td>
<td>1.4 (1.0–1.7)</td>
<td>2.1</td>
<td>1.2 (0.3–2.2)</td>
<td>268</td>
</tr>
<tr>
<td>1030</td>
<td>9.4 (6.4–14)</td>
<td>11 (9.3–12)</td>
<td>45</td>
<td>17 (2.5–17)</td>
<td>111</td>
</tr>
<tr>
<td>1040</td>
<td>3.3 (3.0–3.5)</td>
<td>6.7 (6.2–7.2)</td>
<td>40</td>
<td>4.3 (1.5–6.6)</td>
<td>122</td>
</tr>
</tbody>
</table>
V1486 Ori (COUP #331)

Czesla & Schmitt (2007)

EW = 680 (450-920) eV

$kT > 13$ keV

EW ~ 1400 eV
**Elias 29 (DROXO)**

Giardino et al. (2007,2009); see also Favata et al. (2005)

<table>
<thead>
<tr>
<th>Time interval</th>
<th>( N(H) ) ( \pm )</th>
<th>( kT ) ( \pm )</th>
<th>( f_{6.4\text{ keV}} ) ( \pm )</th>
<th>( W_{6.4\text{ keV}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( N_{22} )</td>
<td>( \text{keV} )</td>
<td>( f_{-6} )</td>
<td>( \text{eV} )</td>
</tr>
<tr>
<td>seg1</td>
<td>5.5 ± 0.7</td>
<td>4.8 ± 1.0</td>
<td>0.1 ± 0.7</td>
<td>34.8</td>
</tr>
<tr>
<td>flare</td>
<td>9.4 ± 2.0</td>
<td>3.9 ± 1.4</td>
<td>2.0 ± 5.9</td>
<td>162.0</td>
</tr>
<tr>
<td>seg2</td>
<td>8.2 ± 1.3</td>
<td>2.8 ± 0.6</td>
<td>1.1 ± 0.6</td>
<td>834.0</td>
</tr>
<tr>
<td>seg3</td>
<td>6.6 ± 0.8</td>
<td>3.3 ± 0.6</td>
<td>0.5 ± 0.5</td>
<td>270.0</td>
</tr>
<tr>
<td>seg4</td>
<td>7.6 ± 0.6</td>
<td>3.6 ± 0.4</td>
<td>0.7 ± 0.7</td>
<td>171.0</td>
</tr>
<tr>
<td>seg5</td>
<td>4.9 ± 0.4</td>
<td>4.5 ± 0.8</td>
<td>1.1 ± 0.8</td>
<td>335.0</td>
</tr>
<tr>
<td>seg3+seg4+seg5</td>
<td>6.4 ± 0.3</td>
<td>3.9 ± 0.3</td>
<td>1.0 ± 0.3</td>
<td>330.0</td>
</tr>
</tbody>
</table>
IRS 43 (DROXO)
The [Ne II] 12.81 μm fine structure line: a tracer of disk gas and of its response to high energy radiation

- Ne 1st and 2nd ionization potentials: 21.56 and 41.0 eV

Glassgold et al. (2007), Mejierink et al. (2008), Gorti & Hollenback (2008), Alexander (2008), Ercolano et al. (2009)
The DROXO field has been observed with high resolution (R~600) Spitzer IRS spectra. Among these, 28 young stellar objects (YSOs) were identified, 25 of which are X-ray sources. Three YSOs were not detected in X-rays, resulting in upper limits on their X-ray luminosities.
Final remarks

- X-ray emission from SFRs is a complex multi-faceted phenomenon (cloud, coronae, accretion, jets)
- High energy phenomena now important for star formation and early stellar evolution
- In the past 10 years *Chandra* & *XMM-Newton* have indeed produced new exciting results
- We have now reached the limits of current instrumentation, and progress will be painful (e.g. for flare analysis, Fe6.4 keV line)