X-rays from classical T Tauri stars
Accretion and wind signatures

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Overview

1. Classical T Tauri Stars
   - Basic Concepts
   - X-ray properties of CTTS

2. Accretion and Outflow signatures
   - Plasma temperatures
   - Plasma densities
   - A common picture?
   - Exceptional X-ray absorption

3. Summary
Evolution of young low-mass 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>Sketch</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age (Years)</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>mm/Infrared Class</td>
<td>Class 0</td>
<td>Class I</td>
<td>Class II</td>
<td>Class III (Class III)</td>
<td></td>
</tr>
<tr>
<td>Disk</td>
<td>Yes</td>
<td>Thick</td>
<td>Thick</td>
<td>Thin or Non-existent</td>
<td>Possible Planetary System</td>
</tr>
<tr>
<td>X-ray</td>
<td>?</td>
<td>Yes</td>
<td>Strong</td>
<td>Strong</td>
<td>Weak</td>
</tr>
<tr>
<td>Thermal Radio</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Non-Thermal Radio</td>
<td>No</td>
<td>Yes</td>
<td>No ?</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

(from Carkner et al. 1998)

**CTTS vs. WTTS**
- H$_\alpha$ EW ($>10\,\text{Å}$)
  - Accretion/Activity
  → usually variable
- IR Class
  - Circumstellar material

⇒ CTTS are actively accreting matter from a circumstellar disk
→ Influence on disk evolution and planet formation
Classical T Tauri stars in X-rays

**X-ray production**

- Magnetic activity (hot plasma, flares)
  ⇒ coronae, star-disk interaction → fluorescence (Fe Kα)
- Accretion shocks (cool plasma, high density)
  ⇒ magnetically funneled e.g. TW Hya (Kastner et al. 2002)
- Confined winds/jets e.g. DG Tau (Guedel et al. 2008)

**X-ray absorption**

- Interstellar + circumstellar material
  ⇒ Requires high-resolution spectroscopy

**Parameter space**: viewing angle, mass, age, accretion/outflow rate, magnetic funnelling, field geometry...
X-ray diagnostics with emission lines

Example: He-like and H-like lines of oxygen

- strong lines, free of blends, but: absorption can be significant
- traces cool plasma regime (2–6 MK)
- O\text{VII}-triplet (21.6–22.1Å): $T_{\text{max}} = 2\text{ MK}$
  - f/i-ratio sensitive to density (and UV-field)
- O\text{VIII} Ly\alpha (18.97Å): $T_{\text{max}} = 3.2\text{ MK}$
### High resolution X-ray spectra of CTTS

<table>
<thead>
<tr>
<th>CTTS</th>
<th>Mission</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP Tau</td>
<td>XMM</td>
<td>Schmitt et al. (2005)</td>
</tr>
<tr>
<td>MP Mus</td>
<td>XMM</td>
<td>Argiroffi et al. (2007)</td>
</tr>
<tr>
<td>RU Lup</td>
<td>XMM</td>
<td>Robrade &amp; Schmitt (2007)</td>
</tr>
<tr>
<td>T Tau</td>
<td>XMM</td>
<td>Guedel et al. (2007)</td>
</tr>
<tr>
<td>TW Hya</td>
<td>Chandra</td>
<td>Kastner et al. (2002)</td>
</tr>
<tr>
<td>V 4046 Sgr</td>
<td>Chandra</td>
<td>Guenther et al. (2006)</td>
</tr>
</tbody>
</table>
X-ray temperature diagnostics: O\textsc{viii}/O\textsc{vii}-ratio

Low O\textsc{vii} ratio (comp. to coronal sources) in all accreting stars
O\textsc{vii} significantly enhanced/O\textsc{viii} marginally enhanced or 'coronal'
⇒ Excess of cool X-ray emitting plasma

Diamonds: Main-sequence stars
(from Ness et al. 2004)

Squares: Herbig AeBe stars

Triangles: Classical T Tauri stars
(Robrade & Schmitt 2007)
X-ray density diagnostics: $\text{O}^{\text{vii}}$ f/i-ratio

- **Active coronal source**
  - $f/i = 2.2$

- **' Typical CTTS**
  - $f/i = 0.34$

- **' Accretional CTTS**
  - $f/i = 0.054$

High plasma densities in **all** low mass ($0.5 - 2.0 \, M_\odot$) CTTS

X-ray emission from accretion shocks and corona
  $\rightarrow f/i$-ratio changes during flares (e.g. BP Tau)
Summary

Plasma temperatures
Plasma densities
A common picture?
Exceptional X-ray absorption

A common picture?

Size of symbols:
excess of cool X-ray plasma

Density depends on stellar mass and radius

Adopting formulae from Calvet & Gulbrin, 1998 and 'free-fall' accretion:

- Accr. density: \( n \sim \dot{M} \times f^{-1} \times (M^{-1/2} R^{-3/2}) \)
- Accr. temp.: \( T_{\text{Shock}} \sim V^2 \sim M/R \)
- Accr. Lum.: \( L_{\text{Acc}} \sim \dot{M} \times M/R \)

Caution: Poor statistics
Exceptional X-ray absorption

The nearly pole-on CTTS RU Lup with absorption seen in the UV (red) vs. X-ray (black); TW Hya similar

'Extra' absorption in several CTTS: optically transparent medium
⇒ wind from star/disk and/or accretion flow
CTTS exhibit a large variety of X-ray phenomena
- Magnetic activity dominates hard X-ray emission
- Accretion contributes to the soft X-ray emission
- Excess of cool plasma in all CTTS
- High densities in all low mass ($\lesssim 2.0 \, M_\odot$) CTTS
- Outflows affect X-ray emission