X-rays from protostars: the holy grail...

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(André et al. 2004)
Outline

1. What is a protostar?
   *From gravitational collapse to young T Tauri stars*

2. Why are X-rays important/essential?
   *Feedback effects on surrounding material*

3. Results from X-ray observations (1)
   *Increasing extinction: From Class II to Class I*

4. Results from X-ray observations (2)
   *From Class I to Class 0*

5. Conclusions and open issues
1. What is a protostar?

- First stage of star formation: collapse of a prestellar core
  - Bonnor-Ebert sphere: see, e.g., B68 (Alves & Lada)
- Central region: “seed” nucleus becoming optically thick.
  - Contraction slows down, surrounding matter “rains” on nucleus
    (process still debated: inside-out? Or external collapse? May depend on external conditions)
- An outflow develops, the central nucleus becomes hot enough to emit cm radiation
  - => jet + disk?
- Observationally:
  - cold (10-20 K => mm) extended envelope + outflow + hot (cm => VLA) source; envelope optically thick (even mm: $A_V >$ few 100)
    - => “Class 0” protostar; phase ~ $10^4$ yrs
  - As a result of accretion, envelope becomes optically thin to mm and IR, revealing central object => IR source;
    - => “Class I” protostar, phase ~ $10^5$ yrs
IRAS 04191 (low-mass Class I)

IRAM 04191 (low-mass Class 0)

(André et al. 2000)
Continuous evolution from collapsing protostars to strongly accreting, young T Tauri stars; Accretion/ejection <=> dominant role of magnetic fields

Class 0 $\rightarrow$ I

Class I $\rightarrow$ II

$\sim 10^4$ yrs $\rightarrow$ $\sim 10^5$ yrs $\rightarrow$ $\sim 10^6$ yrs
2. Why are X-rays important/essential in protostars?

- Feedback irradiation effects on surrounding circumstellar material: ionization, heating, fluorescence
  - Effects on chemistry (=> diagnostics) + heating
- Studied theoretically on disks & jets
  - Provides ionization fraction: \( x_e = n_e/n_p \sim 10^{-9} - 10^{-5} \)
    - (ISM + LECR => \( x_e \approx 10^{-7} \))
  - Effects on cold material: fluorescence (from AGNs)
    - Fe line @ 6.4 keV
- Ionization provides necessary coupling between circumstellar matter and magnetic fields via ambipolar diffusion
- This coupling regulates large-scale accretion vs. ejection in an otherwise neutral environment (e.g., Shu et al., Ferreira et al….)
Disk + jet X-ray irradiation

X-rays

Flare Fe 6.7 keV

Neutral Fe 6.4 keV fluo

Dead zone? (neutral)

GROWING STAR

ACCRETION DISK

0.1 AU

100 AU

Ionized zone

Boston_3T (12-15/7/05) 7
**X-ray effects**

**On disks:** Ionization + fluorescence

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**AGNs:** George & Fabian (1991)

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**On jets:** Contribution to ionization (also heating…)

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**Hsiang et al.** (2002)

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**Igea & Glassgold** (1999)
3. Results from X-ray observations (1)
From Class II to Class I
X-ray light curves of Class I protostars in ζ Oph (XMM)

(Ozawa et al. 2005)
X-ray properties, from Class I to Class III: ρ Oph, XMM

<table>
<thead>
<tr>
<th>Class</th>
<th>kT (keV)</th>
<th>N_H (10^{22} cm^{-2})</th>
<th>E.M. (10^{52} cm^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>2.78 (0.32)</td>
<td>4.52 (0.29)</td>
<td>17.7 (2.4)</td>
</tr>
<tr>
<td>II</td>
<td>2.12 (0.15)</td>
<td>1.48 (0.11)</td>
<td>25.5 (2.9)</td>
</tr>
<tr>
<td>III</td>
<td>1.41 (0.18)</td>
<td>0.81 (0.11)</td>
<td>4.7 (1.1)</td>
</tr>
</tbody>
</table>

(Ozawa et al. 2005)

Boston_3T (12-15/7/05) 11
A triple flare from a Class I protostar: YLW15 in ρ Oph seeing the star-disk central engine?
Ourburst of McNeil’s nebula in Orion, spring 2004: EX Ori-type event in Cl. I?

Very hot gas: evidence for star-disk interactions?
Disk irradiation: fluorescence

• X-rays
  - ionization: coupling with B: jets, etc. (Glassgold et al. 2000)
  - fluorescence? YLW16A (Class I) (Imanishi et al. 2001)
The Magnificent Seven: fluorescing sources in Orion...

See also El29 (Cl. I) in ρ Oph (Favata et al. 2004)

... out of 1616 ! Uncharacterized (Cl. I, II ?)
Jets
Jet-induced X-rays: shock heating

- at the bow shock (HH2, Pravdo et al.)
- at the funnel wall (L1551, Bally et al.)
- + from stellar magnetic activity

Conditions for detection:
- high speed (> 300-400 km s$^{-1}$)
- moderate extinction ($A_V < 50$)
Herbig-Haro objects!

X-rays from HH2: shocked material heated to $\sim 10^6$ K
(Pravdo et al. 2001, Chandra)

*Other case*: L1551
(Favata et al. 2001, XMM
Bally et al. 2002, Chandra)
Reipurth et al. 2003

Infalling envelope

Jet width: ~100 AU

1 AU

Protostars

X-ray reflection

Circumbinary Disk

500 AU

Outflow cavity (~few pc)

Jet cooling zone

Fast [Fe II] emission

Slow [Fe II] emission

X-ray emission

Fast shock

Slow shock

Outflow cavity (~few pc)
4. Results from X-ray observations (2)
From Class I to Class 0
Class I/II sources can be extremely optically thick, mimicking Class 0 sources.

However some IR gets out by scattering => if IR is detected, the envelope is thin and it’s not a Class 0

*X-ray emission may be detected from the jet bowshock(s), if \( N_H \) is not too high there*

\[ A_V > \times 1000 ! \]
Two “candidate Class 0 sources” detected by *Chandra* (Tsuboi et al. 2001) in Orion OMC 2/3 turned out to be high-speed jets (Tsujimoto et al. 2004)
**Class 0 sources are hard to detect!**
(sampling of 11; more expected)

<table>
<thead>
<tr>
<th>Region</th>
<th>Name Cl. 0</th>
<th>Sat.</th>
<th>Exp. (ksec)</th>
<th>D (pc)</th>
<th>Lbol (Lsol)</th>
<th>Lx &lt; (erg/s)</th>
<th>Lx/Lbol &lt; Av=100, T=2 keV</th>
<th>Lx/Lbol &lt; Av=100, T=5 keV</th>
<th>Lx/Lbol &lt; Av=500, T=2 keV</th>
<th>Lx/Lbol &lt; Av=500, T=5 keV</th>
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<tbody>
<tr>
<td>L1448</td>
<td>L1448-C</td>
<td>XM</td>
<td>30</td>
<td>300</td>
<td>9</td>
<td>4.0E30</td>
<td>2.2E-4</td>
<td>1.5E30</td>
<td>8.4E-5</td>
<td>7.6E31</td>
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<tr>
<td>NGC1333</td>
<td>IRAS2,4A,4B</td>
<td>Ch</td>
<td>50</td>
<td>350</td>
<td>40</td>
<td>1.0E30</td>
<td>1.3E-5</td>
<td>3.8E29</td>
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<td></td>
<td>VS13B</td>
<td></td>
<td>7</td>
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<td>7.1E-5</td>
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<td>HH211-MM</td>
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<td>50</td>
<td>300</td>
<td>5</td>
<td>7.7E29</td>
<td>7.7E-5</td>
<td>2.8E29</td>
<td>1.5E31</td>
<td>1.5E-3</td>
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<tr>
<td>Taurus</td>
<td>IRAM04191</td>
<td>Ch</td>
<td>20</td>
<td>140</td>
<td>0.15</td>
<td>4.2E29</td>
<td>1.4E-3</td>
<td>1.5E29</td>
<td>8.1E30</td>
<td>2.7E-2</td>
</tr>
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<td>Ch</td>
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<td>140</td>
<td>2</td>
<td>4.2E29</td>
<td>1.0E-5</td>
<td>1.5E29</td>
<td>8.1E30</td>
<td>1.9E30</td>
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<tr>
<td>L1641-N</td>
<td>VLA1</td>
<td>XM</td>
<td>50</td>
<td>450</td>
<td>50</td>
<td>5.4E30</td>
<td>5.4E-5</td>
<td>2.1E30</td>
<td>1.0E32</td>
<td>2.3E31</td>
</tr>
<tr>
<td>Rho Oph A</td>
<td>VLA1623</td>
<td>Ch</td>
<td>100</td>
<td>150</td>
<td>1</td>
<td>9.6E28</td>
<td>4.8E-5</td>
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<td>L1688</td>
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<td>Ch</td>
<td>30</td>
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<td>1.2E29</td>
<td>2.5E-6</td>
<td>6.2E30</td>
</tr>
</tbody>
</table>

Montmerle et al. in prep. (incl. literature)

Upper limits $L_X/L_{bol} \sim 10^{-5}$ are significant, compared with Class I and TTS detections...
The R CrA region at mm wavelengths (André et al. 2005)

X-ray sources (Hamaguchi et al. 2005)
The “$X_E$” source in R CrA

$A_V \sim 180$

$T \sim 3-4$ keV

$L_X \sim 10^{31}$ erg s$^{-1}$
Massive protostars ?
The BN/KL massive protostar cluster region in the ONC

The BN object is detected (?), but very faint

$A_V \sim 50$, $L_X \sim 10^{29}$ erg s$^{-1}$ (Grosso et al. 2005)
Deeply embedded X-ray sources in OMC-1 South

COUP 632 has $A_V \sim 500$ ! => protostar ? (Grosso et al. 2005)
The Trifid nebula (M20)
\[d \sim 1.7 - 2.8 \text{ kpc}; \text{O7.5}\]

(Rho et al. 2004)
5. Conclusions & open issues (1)

• **Class I protostars: maturing field**
  – many source detections (det. rate > 80 %)
  – a few jets detected (det. rate < 10 %): requires high shock speeds + low extinction
  – + a few examples of fluorescence line (det. rate ~ few %): requires high flux + favorable disk irradiation geometry/viewing angle
  – X-ray properties globally similar to TTS; but higher T

• **Class 0 protostars: many intrinsic obstacles**
  – *Very low detection rate*: 1 detected, combined XMM + Chandra
  – *Very high extinctions*, even for hard X-rays
  – May be eased if viewing geometry favorable (i.e., ~ along funnel); no access to possible soft component
5. Conclusions & open issues (2)

• **Class I protostars**
  – As for Class II TTS, what is the relation between the observed X-rays (magnetic activity) and the large-scale magnetic field channeling the accretion and the ejection?
  – Do the star and the disk necessarily corotate? f(M_*)?

• **Class 0 protostars**
  – First detection very important, but puzzling: L_X comparable to Class I, but very different light curve => special case?
    *But:* the central star does not exist yet!
  – => Is X-ray emission the « birth cry » of stars, i.e., when they start to exist as gravitationally bound bodies, with convection fueling some form of (yet unseen, or non-solar…) magnetic activity?

• **The accretion-ejection phenomenon in time**
  – History? Variable accretion (FUOr or EXOr events)?
  – Magnetic field evolution? (Dynamo, topology, intensity…)