High energy phenomena in young stars

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1. Background: Magnetic activity in PMS stars

2. A first look at the Chandra Orion Ultradeep Project & other recent results

3. A puzzle: No activity/rotation relation in PMS stars

4. X-rays, circumstellar disks & planet formation
Stellar X-rays arise from magnetic reconnection events and thus trace the MHD of stellar interiors and environments.

Yohkoh movies of the X-ray Sun: several weeks (left) and several hours (right)
Model of an X-ray solar flare

Yokohama & Shibata 1998
A contemporary model for protostars & T Tauri stars

Shu et al. 1997, 2001
Why study activity in pre-main sequence stars?

• Ordinary solar-type stars exhibit their highest levels of magnetic activity during their PMS phases

  \[ \log L_x = 30.2 \text{ erg/s} \] for a well-defined sample of PMS solar analogs, compared to \[ \log L_x \approx 27 \text{ erg/s} \] for the contemporary active Sun and \[ \approx 28.5 \text{ erg/s} \] for the most powerful recent flares

  Feigelson et al 2002a, Peres et al 2000

• Large samples of stars can be studied in one field

• Energetic radiation from PMS flares can affect the circumstellar environment
THE *UHURU* CATALOG OF X-RAY SOURCES

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ABSTRACT

A catalog of X-ray sources observed with the *Uhuru* satellite is presented. About 70 days of data have been analyzed for this catalog resulting in 125 sources. Approximately two-thirds of the sources are located within $\pm 20^\circ$ of the galactic plane. Some of the sources at higher galactic latitudes are identified with known extragalactic objects. Most of the strong sources near the galactic plane are found to be variable.

<table>
<thead>
<tr>
<th>Source Name (1)</th>
<th>Location of Maximum Probability Density</th>
<th>Error Region for 90 Percent Confidence</th>
<th>Intensity</th>
<th>Comments and General Remarks</th>
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<td></td>
<td>$\alpha$ (1950) $\delta$ (1950) $b^\Pi$</td>
<td>$\alpha$ $\delta$ (2a) $\delta$ (2b) $\delta$</td>
<td>$\alpha$ (3a) $\delta$ (3b) $\delta$ (3c) $\delta$ (3d)</td>
<td>Area (square degrees)</td>
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<td>In LMC LMC X-2 (7)</td>
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<td>−71 56 24 −72 3 0 −72 6 0 −72 0 36</td>
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<td>82.815 82.815 82.815 82.876</td>
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<td>Tau 1 (3)</td>
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Chandra studies of young low mass stars

**Ophiuchus:** Imanishi et al 2001ab, 2002, 2003; Gagne et al 2003

**Tau-Aur:** Bally et al 2003; Stelzer et al 2003

**Perseus:** Preibisch & Zinnecker 2001, 2002; Getman et al 2002

**Orion:** Garmire et al 2000; Schulz et al 2001; Pravdo et al 2001;
   Tsuboi et al 2001; Feigelson et al 2002ab, 2003; Flaccomio et al 2002,
   2003; Tsujimoto et al 2002; Skinner et al 2003; Grosso et al 2003

**Older dispersed young stars:**
   e Cha Feigelson et al 2003
   B stars Stelzer et al 2003

**D~1-2 kpc star forming regions:**
   Carina Neb Evans et al 2003
   Mon R2 Kohno et al 2002 Nakajima et al 2003
   Cep OB3 Pozzo et al 2003
   IRAS 19410+2336 Beuther et al 2002

+ many studies of massive star formation regions
The Orion Nebula field

Orion Nebula Cluster (ONC) illuminating the HII region M42
Circumstellar disks around Orion PMS stars

HST: Bally/O’Dell
Chandra Orion Ultradeep Project
COUP: Chandra Orion Ultradeep Project

Principal Investigator: Eric Feigelson (Penn State)

Group leaders:

Data reduction & catalog: Kosta Getman (Penn State)**
X-ray spectra & variability: Rick Harnden (SAO)
Optical variability: Keivan Stassun (Wisc)
Origin of T Tauri X-rays: Thomas Preibisch (MPIfR)
Embedded stars: Nicolas Grosso (Grenoble)
Brown dwarfs: Mark McCaughrean (AIP)
Massive stars: Thierry Montmerle (Grenoble)
Effects of X-rays: Francesco Palla (Arcetri)

Participating COUP scientists:

John Bally  Patrick Broos  Paola Caselli  Francesco Damiani
Fabio Favata  Ettore Flaccomio  Gordon Garmire  Alfred Glassgold
William Herbst  Lynne Hillenbrand  Joel Kastner  Charles Lada
Andrea Lorenzani  Gwendolyn Meeus  Giusi Micela  Thierry Morel
Norbert Schulz  Salvatore Scuortino  Hsieh Shang  Beate Stelzer
Leisa Townsley  Yohkoh Tsuboi  Masahiro Tsujimoto  Maureen van den Berg
Scott Wolk  Hans Zinnecker

** see data methods posters by Broos, Getman & Tsujimoto
COUP is constructing an atlas of ~1632 sources

Light curve: 9.8 days exposure spanning 13.2 days

Time-energy plot

JW 45  I=10, K4, M =0.9 Mo, t<<1 Myr

Optical/IR counterpart

0.5-8 keV spectrum with 2-T plasma model

1-T plasma model

Smoothed & energy coded color image

50”x50” image

Polygonal extraction area

Small o = 2MASS
Small + = VLT
A large flare with abundance anomalies
JW 959, K0, M=2 M\(_\odot\), t=1 Myr
A very hot flare with iron excess?
MLLA, K=10
The unusual properties of the nearest & brightest classical T Tauri star: TW Hya

- Main component is soft: kT~0.3 keV
- Abundance anomalies: O, Ne, Fe ~ 0.3 solar
- Density high: Ne IX triplet gives log n~12.8
- Variability: rise < 2ks, decay ~ 15 ks

Soft kT & density suggests accretion origin  
Abund & var suggest flare origin

Chandra HETGS  Kastner et al. 2002
Some flares have extremely long rise & cooling timescales

Contamination by bright source trails

2MASS, K=8
An unusually long & powerful flare in weak-lined T Tauri LkHα 312

Host star: SpTy=M0  Mass~0.7 Mₜ₀  Age~5 Myr  no IR disk or accretion
log Lₓ rises from 30.8 to 32.1 erg/s
kT rises from 1+3 keV to 6 keV and falls to 4 keV
No abundance anomalies
Flare loop models give size h <~ 0.5 R*

Grosso et al. 2003
An extremely absorbed source: \( N_H = 3 \times 10^{23} \text{ cm}^{-2} \) or \( A_V \sim 200 \)

New source in BN/KL region

BN object
Flaring Class I protostars in Ophiuchus

**YLW 16A**
6.4 & 6.7 keV Fe lines

**YLW 16A**
29.5 < \log L_X < 32.0 \text{ erg/s}

**WL 22**
Ca & Ar excess

*Imanishi et al. 2001*
Multiple flares during 13 days are common

2MASS, K=9
Stellar magnetic activity and rotation

Recall for main sequence stars....

Magnetic activity is principally correlated with rotation consistent with solar dynamo theory
For 232 ONC stars with $M<1.5 \, M_\odot$ ...

... the activity-rotation relation is absent!

Feigelson et al. 2003
Same result obtained with Chandra HRC study

Flaccomio et al. 2003
Principal correlates with $L_x$: Mass, $L_{\text{bol}}$ and radius

Flaccomio et al. 2003
Note 2-3 $M_8$ stars with low $L_x$. High $L_x$ stars may be binaries.

Feigelson et al. 2003
Dynamo interpretations

**Standard $a$-W dynamo**
All PMS stars lie in the `supersaturated’ regime?
How do we explain the $L_x$-$L_{bol}$-$R$-$M$ relations?

**Distributed turbulent dynamo**
Recent MHD models of PMS turbulent convective dynamos roughly predict activity is independent of rotation, but more calculations to match correlations are needed.

(Rudiger, Kuker, Stix, Moss, Kitchatinov)

**Change of X-ray behavior at $M>2-3$ $M_\odot$ may reflect dynamo change from full convection to radiative core**
High energy radiation from PMS stars will affect the circumstellar environment

Soft X-rays will be absorbed within $\log N_H \sim 21-23 \text{ cm}^{-2}$ of the star. Each X-ray produces $10^1$ molecular ions which are coupled to B fields and affect astrochemistry. These X-ray Dissociation Regions compete with Galactic cosmic rays in producing low level ionization in molecular clouds.


On interstellar cloud scales, $0.01 < d < 10 \text{ pc}$, estimated integrated X-ray ionization may dominate CRs near young stellar clusters. But no spatial link between PMS stars and ions (e.g. $\text{HCO}^+$) yet seen.

High energy processes in young stellar objects

- Mag field lines
- Cosmic rays
- Proto-Jupiter
- Flare X-rays
- Flare MeV particles
- Dead zone
- Ionized MHD turbulent zone
Possible X-ray effects on disks & planet formation

1. Ionize disk: active turbulent zone vs. dead zone.  
   Jovian vs. terrestrial zones?

2. MHD turbulence promotes accretion & may inhibit planetary migration  
   Hot vs. cold Jupiters?

3. Couple Keplerian orbits to magnetically collimated bipolar outflows

4. MeV flare particles bombard disk solids producing rare isotopes  
   Meteoritic short-lived radionuclides?

4. X-ray flash from flares melts disk solids  
   Meteoritic chondrule formation?

5. X-rays heat outer disk, change chemistry, melt ices  
   IR disk properties (ISO, SIRTF)?

See Feigelson poster on Chandra & planet formation for details.
Conclusions

Much progress from UHURU to Chandra. Rich imaging, spectral, temporal phenomenology in young stellar clusters.

Pre-main sequence stars exhibit a high level of high energy processes from magnetic reconnection with a bewildering variety of X-ray flares.

Activity is linked to $L_{\text{bol}}$ and mass rather than rotation. Evidence for turbulent dynamos?

Flares affect the circumstellar environment, so X-ray studies address: disk turbulence & viscosity; origin of meteoritic isotopes & chondrules; disk heating & chemistry; Jovian planet formation & migration; disk longevity.