An X-ray Outburst from the Accreting Protostar that Illuminates McNeil’s Nebula*

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X-ray emission is a signature property of young, low-mass stars

Chandra X-ray image of the Orion Nebula Cluster
(10-day integration; Feigelson et al. 2004)
BUT:
Is T Tauri X-ray emission diagnostic of coronae, star-disk interactions, or both?

- Evidence for & against coronal origin for X-rays
  - for: flaring, trend of log($L_X/L_*$) with age, $T_X$
  - against: lack of trend of log($L_X/L_*$) with rot. period (but see Stassun et al. 2004, June AJ)

- What about star-disk interactions?
  - X-ray emission predicted theoretically, in magnetospheric accretion model; flaring likely
    - e.g., Shu et al. (1997)
    - strong X-ray flaring observed from very youngest protostars

=> perhaps X-rays can probe evolution of disk-related processes (e.g., accretion)
Enter McNeil’s Nebulous Object...

- Discovered Jan. ‘04 by amateur J. McNeil
  - in NGC 2068 (M78); L1630 dark cloud
- Outburst onset traced to Oct-Nov ‘03
  - increase of ~3 mags (K) to ~5 mags (I) in 1-2 months
  - has since remained in high state (though variable), w/ perhaps very slight decline

- MNO as FU Ori star…or is it an EX Lup type pre-MS star?
  - Either way it’s young, low-mass, & rapidly accreting
Enter McNeil’s Nebulous Object...
(Briceno et al. 2004)

Gemini image, post-outburst (Feb ‘04)
(Aspin & Reipurth, unpublished)
Aside: FU Ori and EX Lup stars

• FUors:
  – Characterized by sudden, spectacular (3-5 mag), prolonged (>10 yr) optical/IR outbursts
  – 3 “prototypes” and ~10 other FUor candidates
    • candidates show disk signatures, massive envelopes

• EXors (ugh...*):
  – More chaotic variability than FUors, w/ smaller, more frequent brightness excursions
  – half a dozen candidates(?)

*Don’t blame me, blame Herbig for “EXor” (but give Herbig a lot of credit, too!)
FU Ori: light curve


"Standard model" (see, e.g., Hartmann & Kenyon's 1996 ARAA paper): sudden accretion rate increase from $10^{-7} \, M_{\text{sun}}/\text{yr}$ to $> 10^{-4} \, M_{\text{sun}}/\text{yr}$ --- star gains $0.01 \, M_{\text{sun}}$ during FUor outburst!
The FUor-like outburst of MNO
Serendipitous, *pre-outburst* detection* of X-rays from the optical/IR/submm source at the “heart” of MNO

*during Nov. ‘02 Chandra imaging of L1630 (Simon et al. 2003)*
Post-outburst:
catching a contemporaneous X-ray eruption
via Chandra DDT “quick looks”

Serendipitous detection by CXO (Nov. ‘02)

CXO DDT observations
(March ‘04)
MNO in outburst: a (relatively) hard X-ray source

Model (watch out... only ~50 photons!):
- $N_H \sim 6 \times 10^{22} \text{ cm}^{-2}$
- $T_X \sim 6 \times 10^7 \text{ K}$

Image and spectrum from March 7 CXO DDT data
What does MNO tell us about the nature of X-rays from pre-MS stars?

- **In at least SOME cases, X-rays can be generated via pre-MS accretion processes**
  - But $T_x$ of MNO source too high to be explained by accretion shocks... $\Rightarrow$ X-rays from magnetospheric reconnection events, probably intimately related to (responsible for?) “fresh” outflow activity
    - MNO source lies at end of HH 23 knot chain

- **In that case, why aren’t all FUors bright X-ray sources***?
  - Perhaps FUor accretion “flood” eventually “quenches” magnetospheric reconnection processes

*only 2 known X-ray sources (e.g., L1551 IRS5); both are weak*
Next steps: continued X-ray monitoring of MNO (we hope…)

- XMM: 40 ks DDT observation obtained
  - April ‘04: source remains bright & highly variable
- CXO: another 3x20 ks campaign proposed for Cycle 6
Does Orion hold additional clues?

Spectral/temporal analysis of 1600+ sources in the ONC should provide new insight into X-ray emission processes...
...stay tuned for results from COUP!

Chandra X-ray image of the Orion Nebula Cluster
(10-day integration; Feigelson et al. 2004)
Empirical solar/stellar B-L$_X$ relation

X-ray spectra soften from the T Tauri stage to the main sequence

Left: ROSAT HRs for Taurus TTS; nearby 10 Myr-old stars; the Hyades; and MS stars

Above: ROSAT hardness ratios for the TW Hya Association

The (spectroscopic) power of Chandra

Chandra/HETG spectrum demonstrates that the X-ray spectrum of TW Hydrae displays bright emission lines...of Ne!
Chandra spectroscopy of cTTS TW Hya: Evidence for accretion

Ne IX:
R I F

CXO/HETG spectra

log n ~ 13

Coronal sources:
log n ~ 10-11

Magnetospheric accretion model
Observing a “control”: the quadruple weak-lined TTS system HD 98800

Left: Keck mid-IR imaging (Prato et al. 2001)

Right: CXO/HETG 0th-order X-ray image (data obtained March, 2003)

Caught in the act: a flare on HD 98800 A
TW Hya vs. HD 98800 in X-rays: Accretion vs. coronal activity?

TW Hya:
- high density,
- low Fe/Ne,
- “cool”

HD 98800:
- low density,
- larger Fe/Ne,
- “hot”
X-ray spectroscopy as diagnostic of accretion vs. coronal activity in TTS?
Perhaps, but...more hi-res data needed!

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\begin{align*}
\text{cTTS:} & \quad \log n \sim 13^* \\
\text{wTTS and active MS stars:} & \quad \log n \sim 10-11
\end{align*}
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*are TW Hya line ratios indicative of high density or strong UV?