Episodic Accretion in Young Stars

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Sources of Variability

• Intrinsic luminosity changes (this talk)
• Variable extinction (flared disks, periodic obscuration)
On the Episodic Outbursts of Young Stars

-Does episodic accretion play an important role in star formation?
  -Archetypal sources FU Orionis and EX Lupi
-How has our understanding of these objects changed since 1996, observationally?
-How has our understanding changed theoretically?
  -Are FUors/EXors evidence of episodic accretion?
  -Are FUors/EXors the same class of objects?
The FU Orionis Eruption: 1936

Hartmann & Kenyon, 1996, ARAA, 34, 207

Courtesy: C. Briceno


Much wider than blackbody
Additional FUors 1950-1978

Protostar to Protoplanetary Disk: the Nature of Accretion

\[ \frac{dM}{dt} \text{(wind)} \sim 0.1 \frac{dM}{dt} \text{(acc)} \]

\[ \frac{dM}{dt} \text{(infall)} \sim 10^{-5} \]

\[ \frac{dM}{dt} \text{(disk)} \sim 10^{-4} - 10^{-7} \]

Modified from Hartmann & Kenyon, 1996, ARAA, 34, 207
• Steady accretion model + hot inner disk extending from 5 $R_\odot$ to 0.5-1 AU
• Decay timescale: $t_{\text{visc}} \sim R^2/\nu \Rightarrow \alpha \sim 0.01-0.1$
How significant are the bursts?

(Updated from Hartmann & Kenyon, 1996, ARAA, 34, 207)

**FUors are rarely seen... but they are common events!**

Within 1 kpc of the Sun:

$10^4 - 10^5$ T Tauri stars x avg. accretion rate $10^{-8} \, M_\odot \, yr^{-1} = 10^{-3} \, M_\odot \, yr^{-1}$

8 FUors, combined accretion rate $\sim$ few $x \, 10^{-4} \, M_\odot \, yr^{-1}$

-FUors are responsible for $\sim 10\%$ of the current nearby accretion

About 8 FUors since 1936; average star formation rate $1 / 50 \, yr$


-FUors occur at several times the rate of star formation; averaging multiple bursts per star
EX Lup: Multiple Bursts

1955: EX Lupi was seen to outburst to a somewhat lesser degree, and much shorter timescale, and was referred to as an “EXor” (Herbig, 1989, ESO Workshop, 233)

And again in 2008: Ábrahám et al., 2009, Nature, 459, 224
Why study these sources?

• Represent stages wherein most of the YSO mass may be accumulated
• Accretion mechanism may differ from the classical magnetospheric TTS accretion model: "new" accretion physics
• Diagnostic for outburst triggering mechanisms, an important problem
• Offer "unveiled" examples of YSOs with accretion rates comparable to embedded sources
EXors and FUors are a Natural Laboratory for Accretion Physics

Ábrahám et al., 2009, Nature, 459, 224

Courtesy: R. Hurt, SSC
FUors vs. EXors, observationally

• Commonalities:
  – low mass pre-main sequence stars
  – Show strong optical outbursts
  – IR excess indicating circumstellar disk material (gas and dust)
  – Variability is primarily* accretion-driven

EXor Timescales Allow Characterization of the Complete Burst

Herbig G. H., 1977, AJ., 217, 693
FUors vs. Protostars

Previously noted similarities at submillimeter wavelengths (e.g. Sandell & Weintraub, 2001, ApJS, 134, 155);

Consistent with the Spitzer/Herschel perspective

Green et al., in prep.

<table>
<thead>
<tr>
<th>Characteristic Properties, Classically</th>
<th>FUor (all remain in outburst)</th>
<th>EXor (during outburst)</th>
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</thead>
<tbody>
<tr>
<td>Optical burst strength</td>
<td>4-6 mag; 20-500 $L_\odot$</td>
<td>3-5 mag; 0.5-20 $L_\odot$</td>
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<tr>
<td>Optical line profiles</td>
<td>Fe I, Li I, and Ca I double-peaked/broadened profiles</td>
<td>Infall and outflow signatures in Na I D$_{1,2}$ – like CTTS (P Cygni profiles)</td>
</tr>
<tr>
<td>Repeated burst?</td>
<td>Not in human timescale</td>
<td>Yes ~ 1/few yrs</td>
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<tr>
<td>IR line profiles</td>
<td>first-overtone</td>
<td>CO bandhead emission and absorption, variable</td>
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<td></td>
<td>CO absorption at 2.2 μm;</td>
<td></td>
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<tr>
<td></td>
<td>double-peaked profiles</td>
<td></td>
</tr>
<tr>
<td>Inferred accretion rates</td>
<td>&gt; $10^{-6}$ –$10^{-4}$ M$_\odot$ yr$^{-1}$</td>
<td>$10^{-7}$ –$10^{-5}$ M$_\odot$ yr$^{-1}$</td>
</tr>
<tr>
<td>Extended reflection nebula?</td>
<td>Yes</td>
<td>Sometimes</td>
</tr>
<tr>
<td>Spectral type</td>
<td>F-M, wavelength dependent</td>
<td>K-M</td>
</tr>
<tr>
<td>Pre-Main Sequence Stage; envelope?</td>
<td>I/II</td>
<td>II ?</td>
</tr>
<tr>
<td>Crystalline silicates</td>
<td>No</td>
<td>During outburst</td>
</tr>
<tr>
<td>Burst rise time</td>
<td>0.3-10 yr</td>
<td>~ 0.1-0.3 yr</td>
</tr>
<tr>
<td>Burst decay time (e-folding)</td>
<td>&gt; 20-100 yr</td>
<td>0.5-2 yr</td>
</tr>
</tbody>
</table>
FUor Subgroups

“Embedded”

“Flared Disk”

Inclination effect?

Figure from Quanz et al., 2007, ApJ, 668, 359; see also Green et al., 2006, ApJ, 648, 1099
New Outbursts
The Case of V1647 Ori

One year after return to quiescence


V1647 Ori/ McNeil’s Nebula
Meanwhile, in Cygnus...

August 17, 2010: Semkov & Peneva (2010), ATel, 2801, announces outburst
September 24: HBC 722/V2493 Cyg reaches maximum light and begins decaying

Region in between the North America & Pelican Nebulae, distance 520 pc

Nearly Simultaneously, an EXor with a slow rise time but fast decay time

V2492 Cyg
Kóspál et al., 2011, A&A 527, 133
The Distinction via Lightcurve is Becoming Less Straightforward

Based on data from Kóspál et al., 2011, A&A, 527, 133 and from AAVSO

Difficult to classify outburst type from early behavior!

Hartmann & Kenyon, 1996, ARAA, 34, 207
Can X-rays Distinguish Between EXors and FUors? Do X-rays follow accretion processes?

For V1647 Ori, yes

.... But not for V1118 Ori

Weak correlation between X-ray and IR (also for EX Lup)

Audard M. et al. (2005) AJ, 635, L81

At least *some* (soft) X-rays in EXors arise in accretion shocks
X-Rays from FUors

- FUors are X-ray bright, compared to X-ray active T Tauri stars, but not relative to the total system output
- Multiple (hard and soft) X-ray components sometimes seen but can be attributed to binaries?

Hard X-rays = magnetically-driven
Soft X-rays = accretion processes

e.g. Grosso et al. 2010, A&A 522, A56


- 1-day periodicity stable over five yr
- (caveat: flux amplitude is relative)
- Star/disk magnetospheric geometry is highly stable
Detailed model of the disc–star interaction and the formation of a conical wind. The wind/outflow base originates very close to the stellar photosphere.

- Infalling matter compresses the magnetosphere of the star
- Field lines enhanced via differential rotation between disk and star
- Conical winds & outflows twist from the inner disk


Figure from Königl A et al. MNRAS 2011;416:757-766
The Mid-IR: Long-Term Outburst Effects

Does dust processing from flash heating (or vertical transport and stirring of dust grains) occur on few month timescales?
What sets the conditions in the protoplanetary disk?

• In the usual paradigm, the Class I protostar lifetime is \( \sim 0.5 \) Myr, during which the envelope thins and eventually vanishes.

• The accretion rate from disk to star diminishes and planets form, perhaps early on by gravitational instability, and then later by core accretion, and other processes.

• But does accretion decrease steadily from \( 10^{-5} \) in Class I to \( 10^{-8} \) in T Tauri stars, to \( 10^{-10} \) or less in Class III sources?
Empirical Prediction $\rightarrow$ New Accretion Paradigm


Magnetorotational + Gravitational Instability Model (MRI+GI)

GI: Outer Disk: Q~1
MRI: Inner Disk (hot/ionized)
Transition region: (1-10 AU) GI-MRI junction not smooth => episodic accretion
Predicts correct outburst strength and timescale
But the details of MRI triggering are uncertain

Martin & Lubow 2011, AJ, 740, 6

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Accretion bursts due to disk fragmentation in the embedded phase

If Toomre parameter $Q \leq 1.0$ and disk cooling is fast ($\Omega \times t_c < \text{a few}$), disk fragmentation can occur (e.g. Gammie 2001, ApJ, 553, 174)

Face-on view on the inner 400x400 AU, The total computational box is 10 times larger.

Black regions are not empty but filled with infalling envelope (off the scale)

protostellar accretion rate $10^{-5} M_\odot / \text{year}$

Modeled Outburst Frequency via Disk Instability

EX Lup (AAVSO; 1955-2010)

Or binary companion?


Outbursts affect chemistry

CO-gas phase fraction in the envelope steeply rises during the burst and gradually declines after the burst. The relaxation time to the pre-burst stage is notably longer than the burst duration.

Looking forward: what are the contributions of the FUor/EXor observational group to our understanding of young stars?
Looking forward (1)

• Are FUors and EXors regularly occurring events, or are they special cases of young stars?
  – Evidence for episodic accretion comes from both observation and theory
    • Observed burst frequencies, accretion rates, lifetime estimates from decay times all match the idea that 5-10% of total YSO accretion occurs in FUor bursts
    • Offer a partial solution to the transport of newly crystallized small dust grains in disks
    • Theory of duty cycles from episodic accretion models agrees with observed timescales
    • Chemical evolution models (increased CO gas abundance, CO$_2$ ice processing in currently low luminosity stars)
    • Outflow morphology (bullets, multiple epochs)
Looking forward (2)

• Are FUors and EXors different classes?
  – Clear distinction has blurred through intermediate cases like V1647 Ori, V2492 Cyg, and HBC 722
  – Primary remaining distinction is the timescale
The Future of Episodic Accretion Studies

- ALMA continuum/line imaging -> envelope vs. disk masses -> evolution stage
- Comprehensive large-field monitoring facilities (PTF, LSST) to detect new eruptive stars early in outburst
- WISE will help detect new sources, more deeply embedded eruptive stars
The Next Step

• Move away from FUor vs. EXor classification
• Modeling to better understand accretion burst mechanisms
• Identify key parameters controlling bursts
• These objects are no longer oddities, but fundamental to the analysis of the evolution of young stars!