Episodic accretion in star formation

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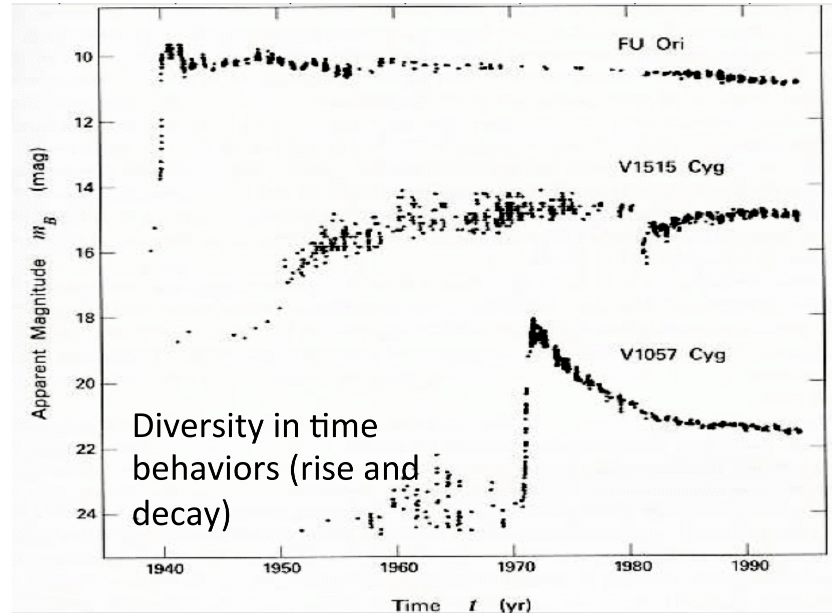
Outline

- The FU Ori phenonemon
  - Classical objects and their properties
  - EXors outbursts
  - Recent outbursts and their implications
  - Impact of episodic accretion
- Models for episodic accretion
- Relations to star and planet formation
- Conclusions and future prospects

See recent review for PPVI:
Audard et al. (2014)

Classical FUors



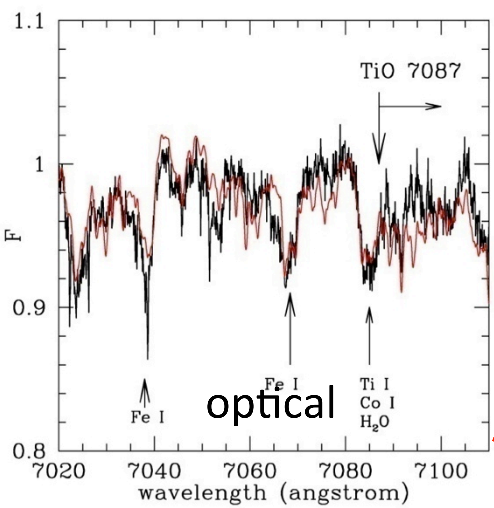
Several stars with similar properties to FU Ori were discovered → "classical" FUor group (Herbig, 1977; Elias 1978).

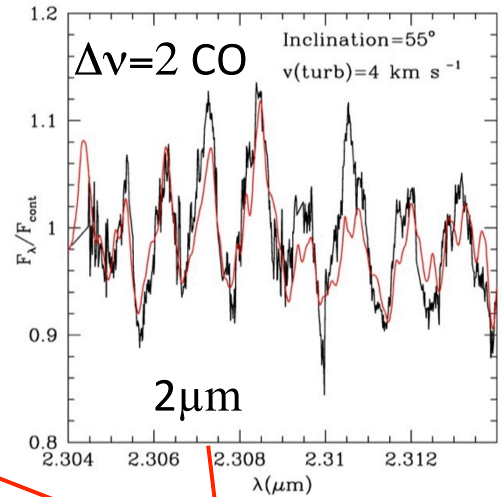
FUor-like objects classified for having spectra similar to FU Ori, without having the outburst effectively observed (Reipurth et al. 2002; Reipurth & Aspin 1997; Greene et al. 2008)

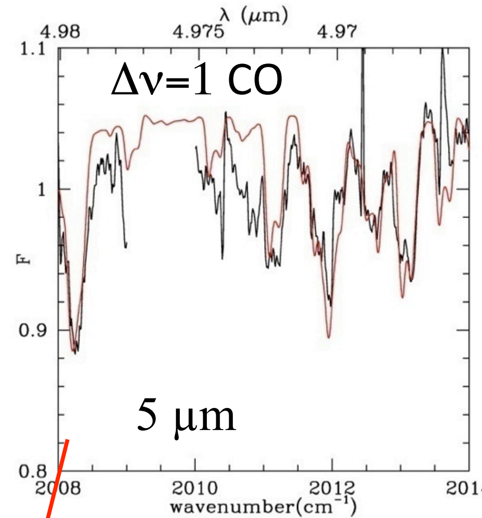
FUOr properties

- Eruptions with brightening by 2-7 magnitudes with long outburst durations (>10 yrs), possibly repetitive
- Optical nebulosities around them
- F or G-type supergiant spectra in the optical
- K or M-type supergiant spectra in near-IR
- Strong CO bandheads in absorption (Reipurth & Aspin 1997)
- Sudden increase in mass accretion rate onto star (10^{-7} to 10^{-4} M_{sun} yr^{-1}, see Hartmann & Kenyon 1996 review)
- Infrared excess indicating disk/envelope surrounding material

Accretion disk model (Kenyon & Hartmann 1991)

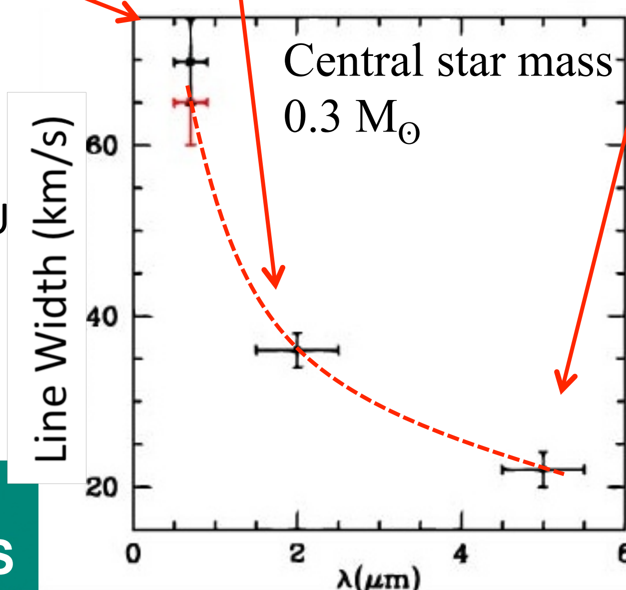


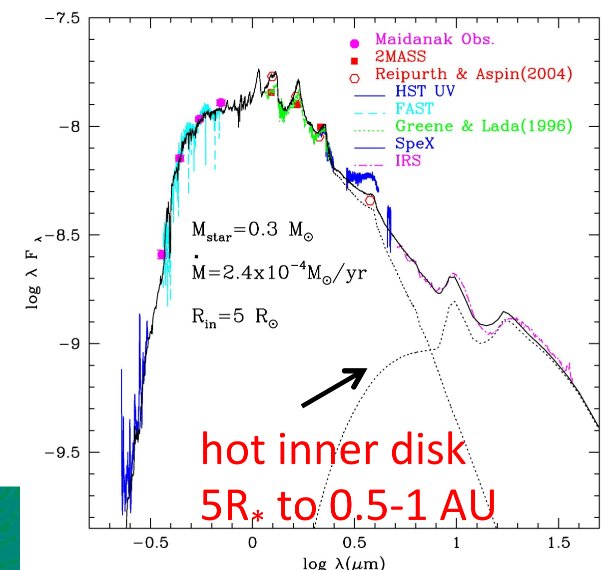




(Zhu et al. 2007; 2009)

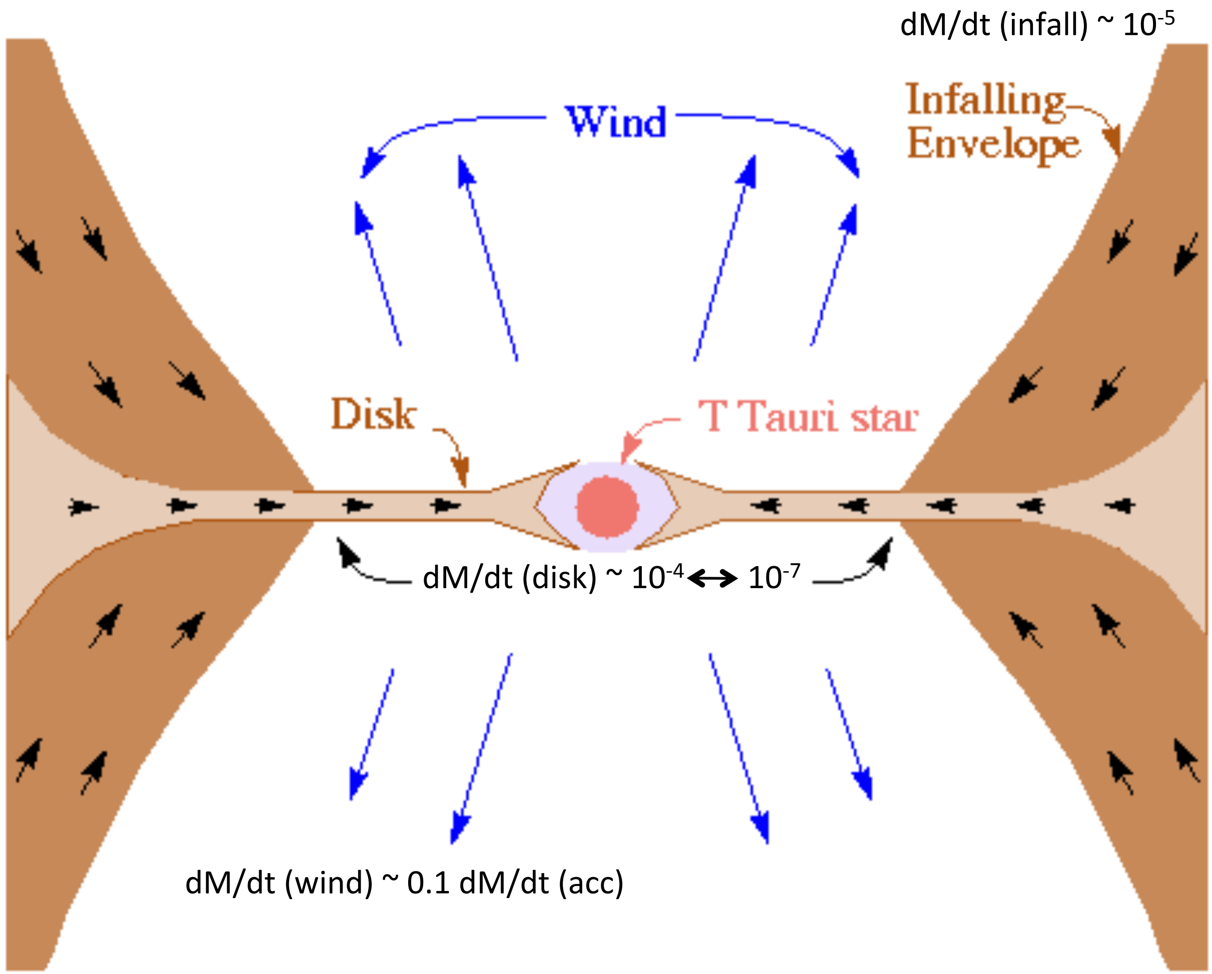
- Double peak profiles in optical and infrared (< 10μm)
- Keplerian rotation disk to 0.5 AU





Adapted slide from Z. Zhu

Protostar/FU Ori object/T Tauri star

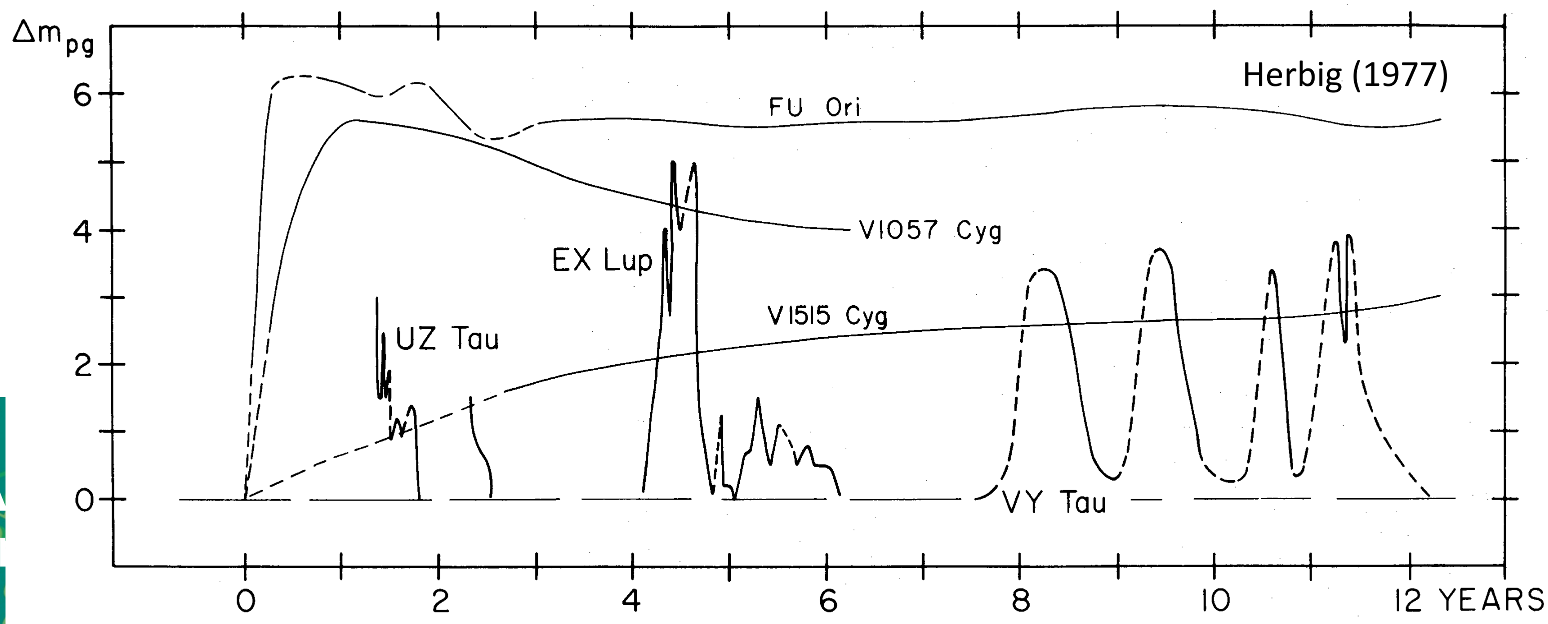


The EXor class of eruptive young stars

EXor stars (after EX Lup) show weaker outbursts (ΔV≈2-3 mag) and of shorter duration (a few months to years). See Herbig (1977, 1989)

- Progenitor often M-type “normal” CTTS star
- Outburst spectra show emission lines, CO bandhead in the near-IR in *emission*
- IR excess indicating circumstellar matter (disk, possibly envelope)

→ association with mass accretion rate increases, but it remains unclear if the mechanism driving the episodic accretion is similar or different from FUors



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

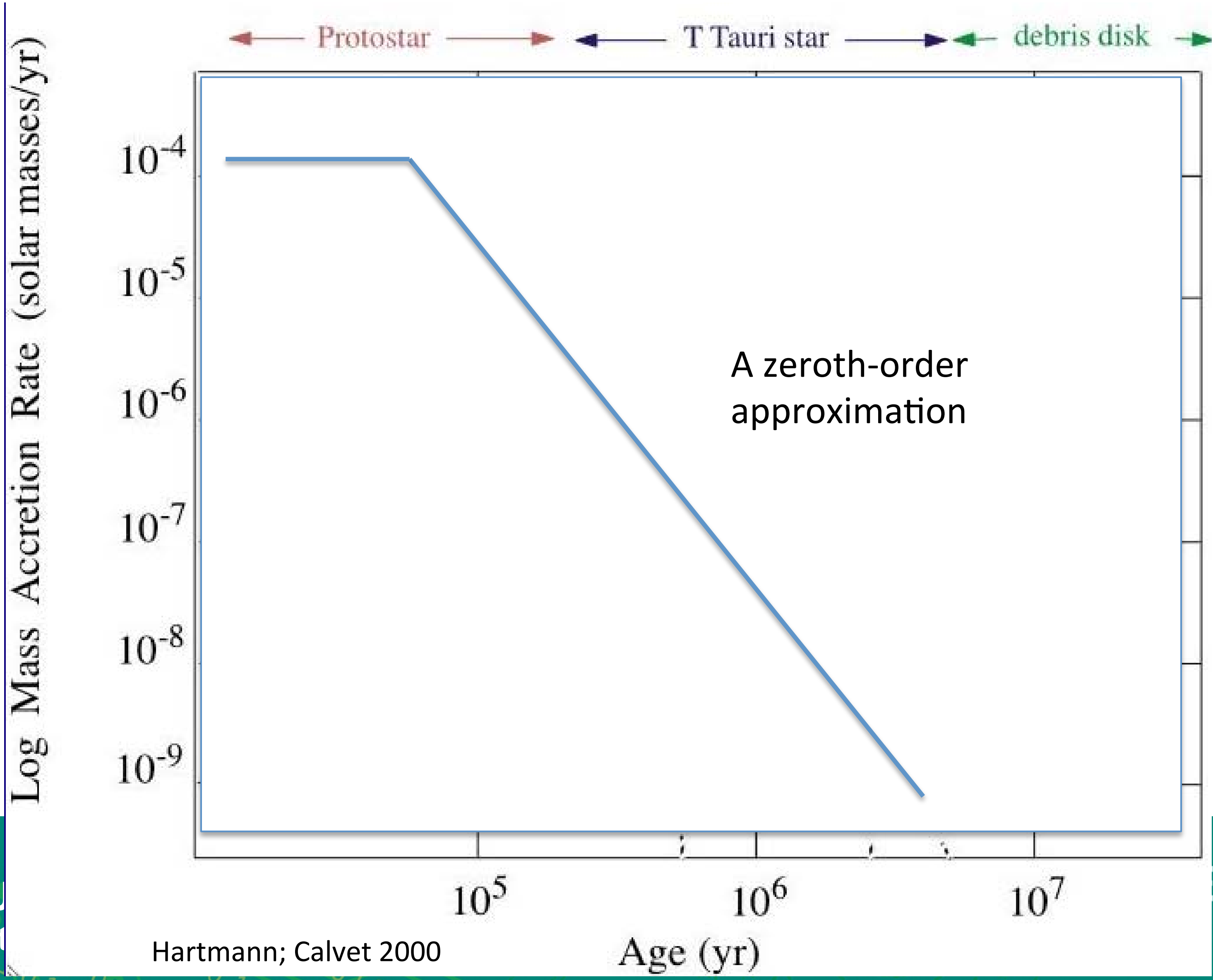
Slide by J. Green, PPVI

A (non-exhaustive) list of erupting young stars

Audard et al. (2014, PPVI review)

Name	Type	Distance (pc)	Onset (yr)	Duration (yr)	A_V (mag)	$L_{\rm bol}$ ($L_\odot$)	$\dot{M}_{\rm acc}$ ($M_\odot$ yr^{-1})	Companion
RNO 1B	FUor-like	850	...	>12	9.2	...	...	Y (RNO 1C, 4")
RNO 1C	FUor-like	850	...	...	12.0	...	...	Y (RNO 1B, 4")
V1180 Cas	EXor?	600	2000, 2004	2.5, 7	4.3	0.07 (L)	>1.6e-7 (L)	Y? (6.2")
V512 Per	EXor	300	>1988, <1990	>4	...	66 (L)	...	Y (0.3")
PP13S	FUor-like	350	...	...	~40	30	...	N?
XZ Tau	EXor?	140	1998	>3	1.4	0.5	1e-7	Y (0.3")
UZ Tau E	EXor	140	1921	0.5?	1.5	1.7	1−3e-7	Y (SB+4")
VY Tau	EXor	140	many	0.5−2.0	0.85	0.75	...	Y (0.66")
LDN 1415 IRS	EXor?	170	>2002, <2006	...	...	>0.13 (L)	...	...
V582 Aur	FUor	...	>1984, <1986	>26	...	...	...	...
V1118 Ori	EXor	414	2004,many	~1.2	0−2	1.4 (L), 7−25 (H)	2.5e-7 (L), 1e-6 (H)	Y (0.18")
Haro 5a IRS	FUor-like	450	...	...	22	50	...	...
NY Ori	EXor	414	many	>0.3	0.3	...	...	N
V1143 Ori	EXor	500	many	~ 1	...	...	...	...
V883 Ori	FUor-like	460	...	...	...	400	...	...
Reipurth 50 N IRS 1	FUor-like	460	...	...	...	300	...	...
V2775 Ori	FUor-like	420	>2005, <2007	> 5	8−12	2-4.5 (L), 22-28 (H)	2e-6 (L), 1e-5 (H)	Y? (11")
FU Ori	FUor	450	1936	~100	1.5−2.6	340−500	...	Y (0.5")
V1647 Ori	EXor?	400	1966,2003,2008	0.4−1.7,2.5,>4.3	8−19	3.5−5.6,34−44	6e-7,4e-6−1e-5	...
AR 6A	FUor-like	800	...	>13	18	450	...	Y (AR 6B, 2.8")
AR 6B	FUor-like	800	...	...	>18	...	...	Y (AR 6A, 2.8")
V900 Mon	FUor-like	1100	>1953, <2010	>16	13	106 (H)	...	N
Z CMa	FUor	930−1100	many	5−10	1.8−3.5	400−600	1e-3	Y (0.1")
BBW 76	FUor-like	1700	<1900	~40	2.2	287	7.2e-5	N
V723 Car	EXor	...	...	...	...	...	...	...
GM Cha	EXor?	160	many	>1.9	$\gtrsim$13	>1.5	1e-7	Y (10")
EX Lup	EXor	155	2008,many	<1	0	0.7,2	4e-10,2e-7	Y? (BD)
V346 Nor	FUor	700	~1980	>5	>12	135	...	N
OO Ser	FUor-like	311	1995	>16	42	4.5 (L), 26-36 (H)	...	N
Parsamian 21	FUor-like	400	...	...	8?	3.4, 10	...	N?
V1515 Cyg	FUor	1000, 1050	~1950	~30	2.8−3.2	200	3.5e-5	...
PV Cep	EXor?	325	repetitive	~ 2	12.0	41 (L), 100 (H)	2e-7−2.6e-6 (L), 5.2e-6 (H)	...
V2492 Cyg	EXor?	600	>2009, <2010	>3	6−12, 10−20	14 (L), 43 (H)	2.5e-7 (H)	...
HBC 722	FUor	600	2009	>4	3.4, 3.1	0.7−0.85 (L), 8.7−12 (H)	1e-6 (H)	...
V2494 Cyg	FUor-like	700−800	>1952, <1989	>20	5.8	14−18	...	...
V1057 Cyg	FUor	600, 700	1970	~10	3.0−4.2	250−800	4.5e-5	N
V2495 Cyg	FUor	800	1999	>8	...	...	...	...
RNO 127	FUor	800	1999	>6	...	...	...	...
V1735 Cyg	FUor	900	>1957, <1965	>20	8.0−10.8	235	...	Y? (20-24")
HH 354 IRS	FUor-like	750	...	...	...	73.0	...	...
V733 Cep	FUor-like	800	>1953, <1984	>38	8	135 (H)	...	...

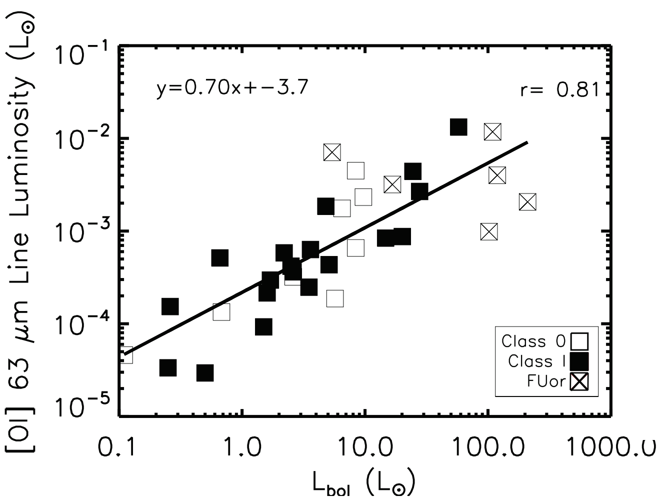
Accretion rate history

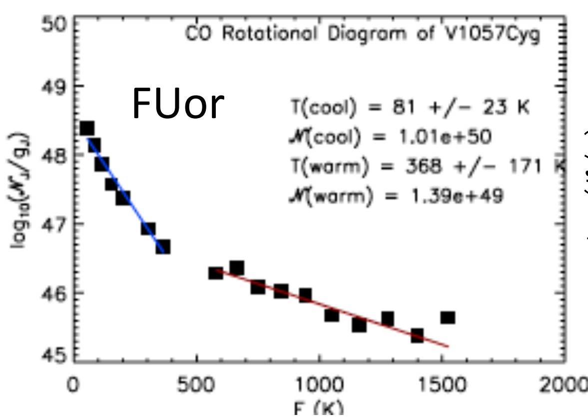


Hartmann; Calvet 2000

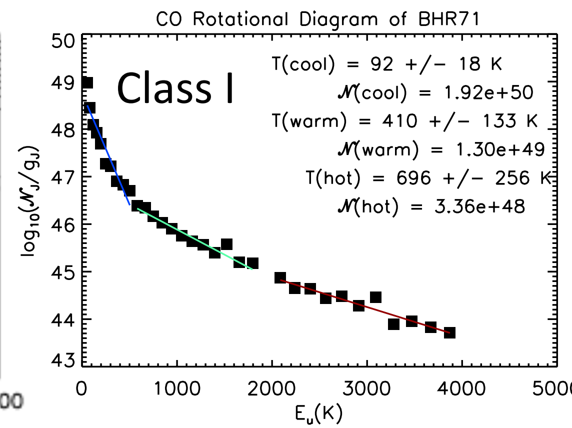
FUors and protostars

- Previous far-IR and submm studies suggested similarities between FUors and protostars (e.g., Sandell and Weintraub 2001; Lorenzetti et al. 2000)
- Recent Spitzer and Herschel studies also show similarities (e.g., Quanz et al. 2007; Green et al. 2006; 2013; 2014) but not necessarily for CO warm emission (except V1057 Cyg)



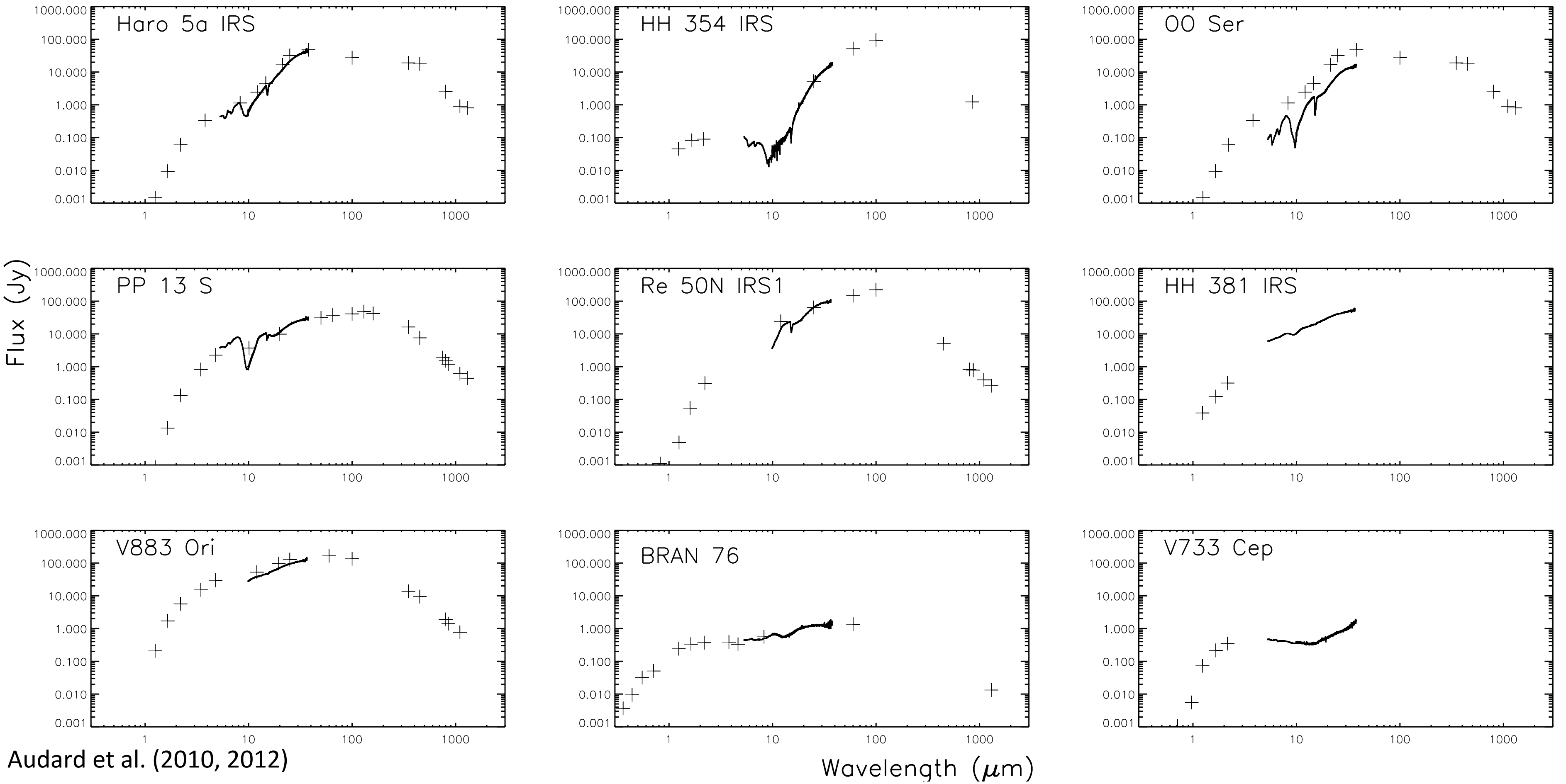


Green et al. (2013)



Green et al. (2014)

FUor spectral energy distributions



Audard et al. (2010, 2012)

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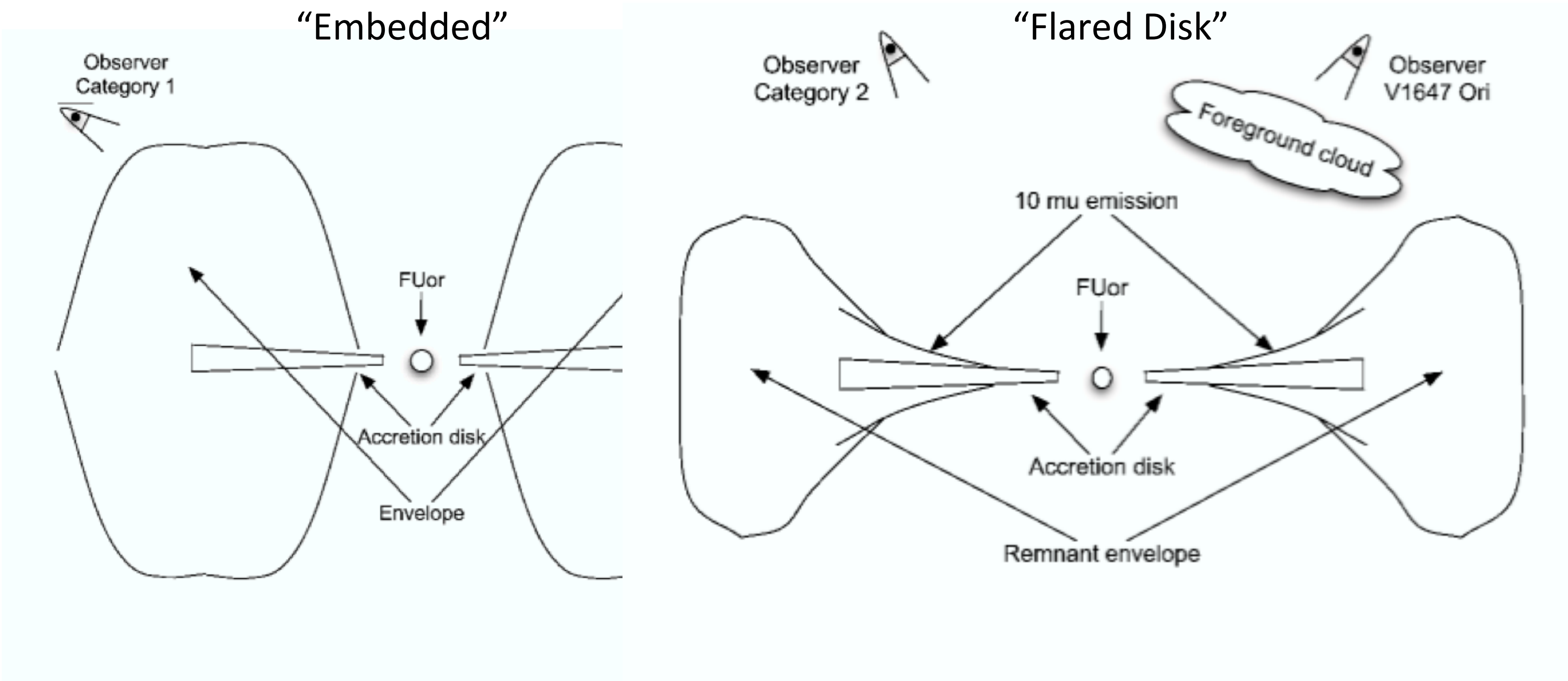
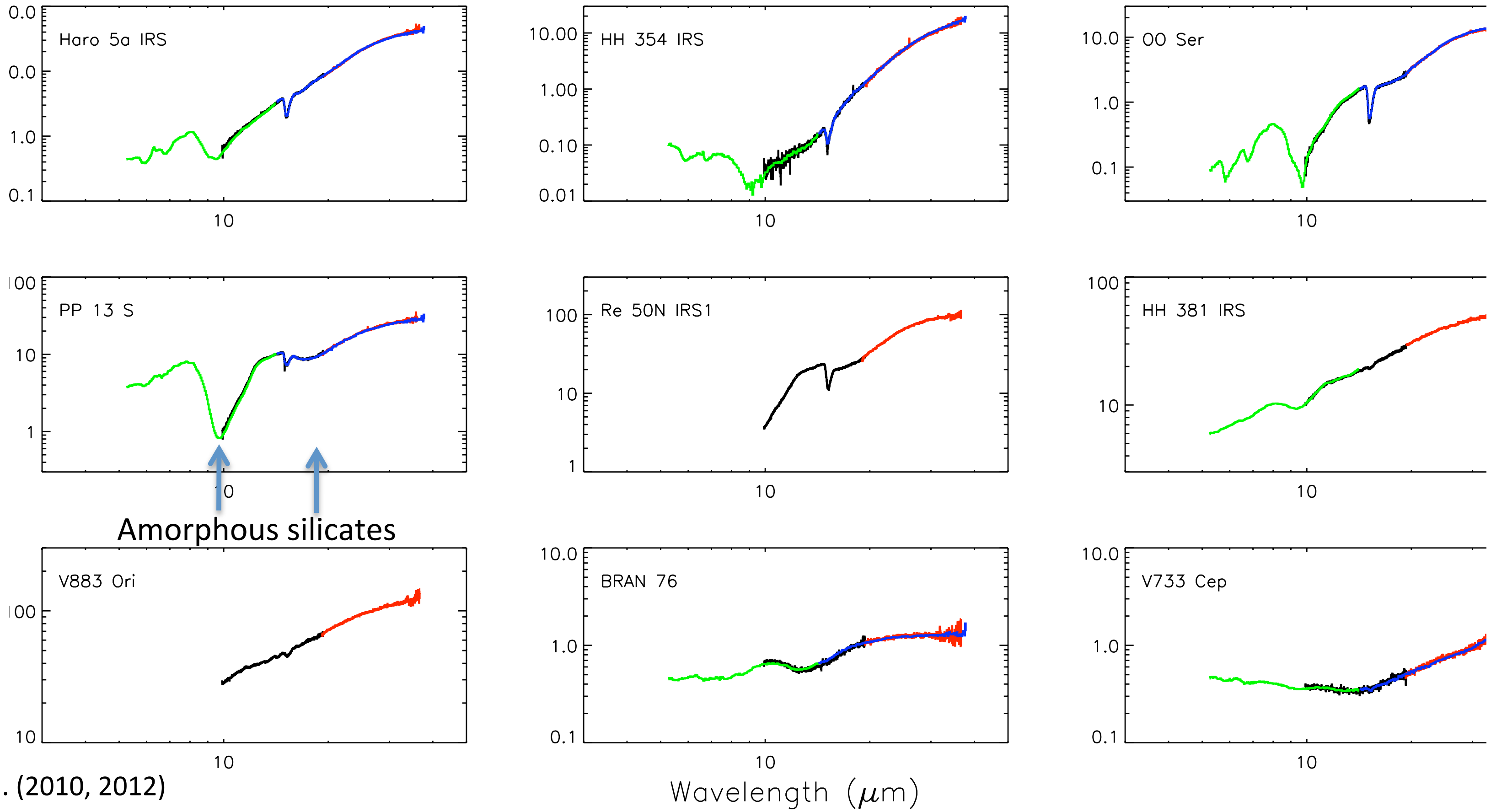
FUor subgroups → evolutionary stages?



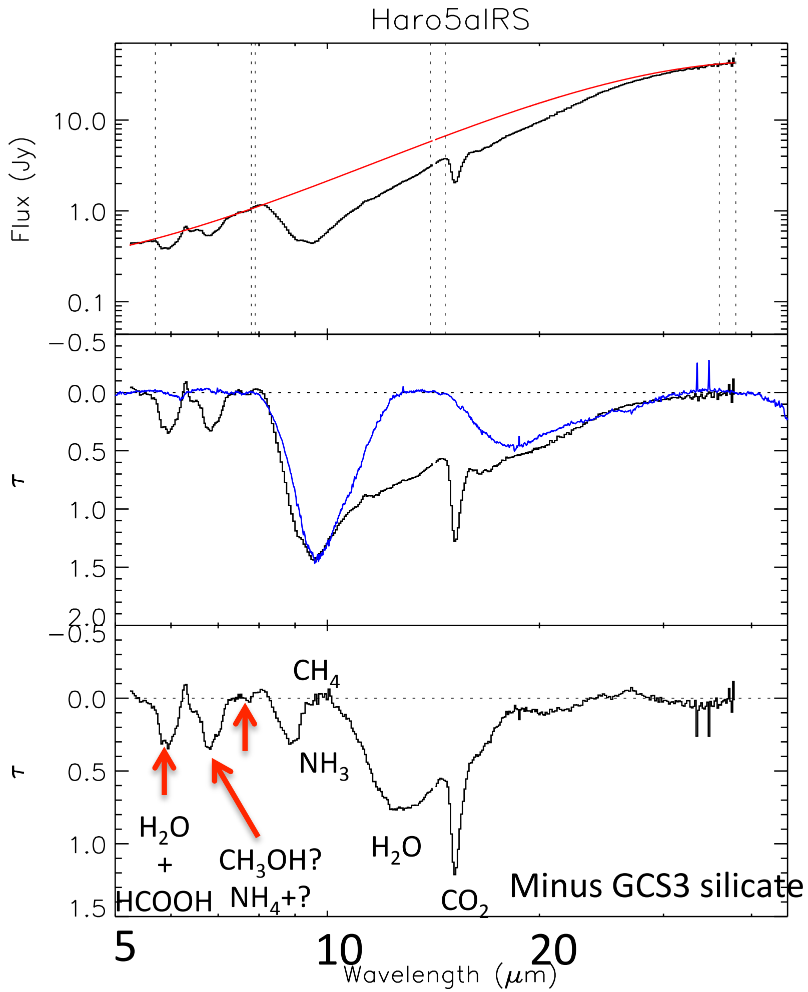
Quanz et al. (2007), see also Green et al. (2006)

Mid-infrared spectra of FUors



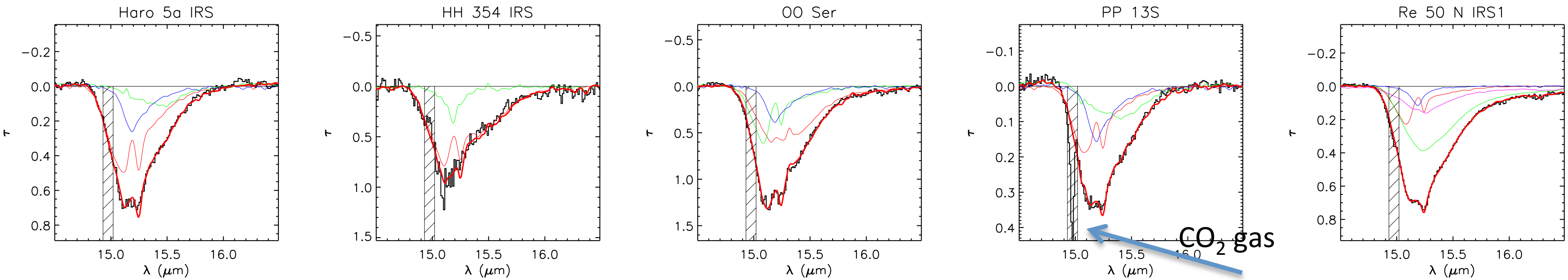
Audard et al. (2010, 2012)

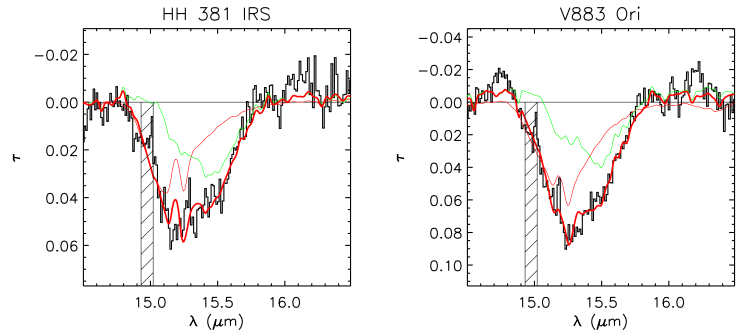
Ices in embedded FUors



Audard et al. (2010, 2012)

Ices in embedded FUors





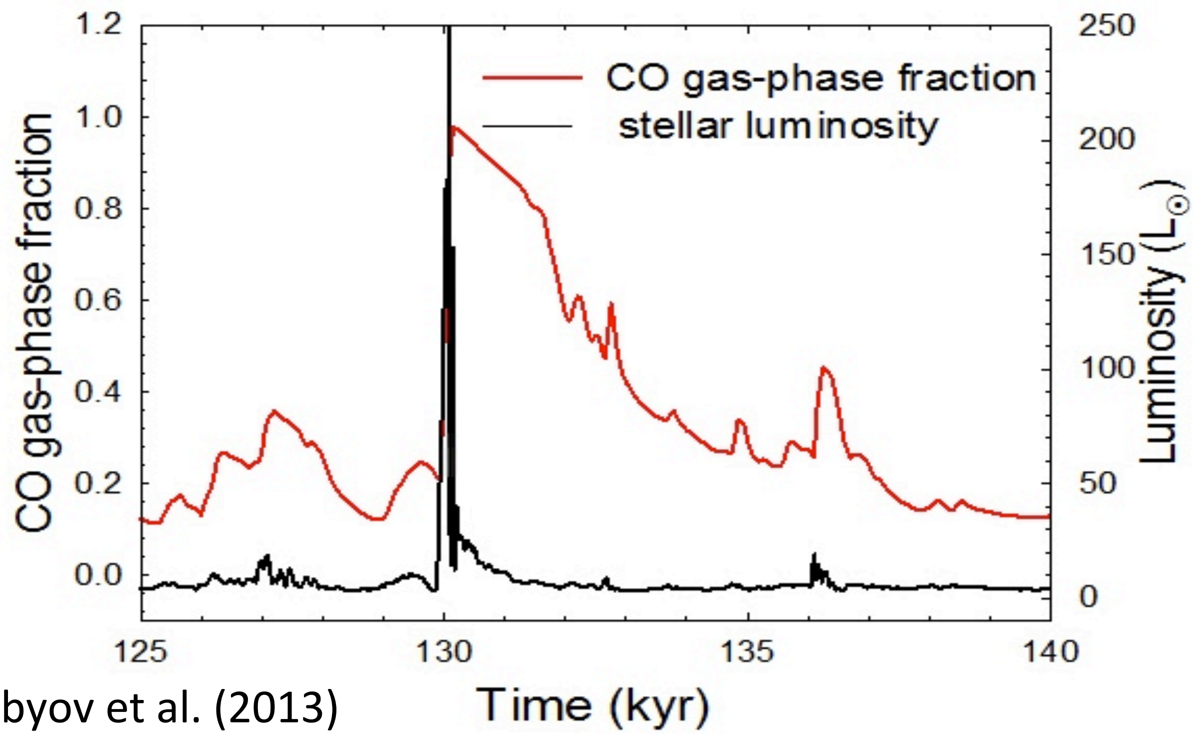
$H_2O+CH_3OH+CO_2$ mixtures from White et al. (2009)

Audard et al. (2010, 2012)
See also Quanz et al. (2007), Kim et al. (2012)

→ presence of “pure” CO_2 ices and other mixtures

Outburst chemistry

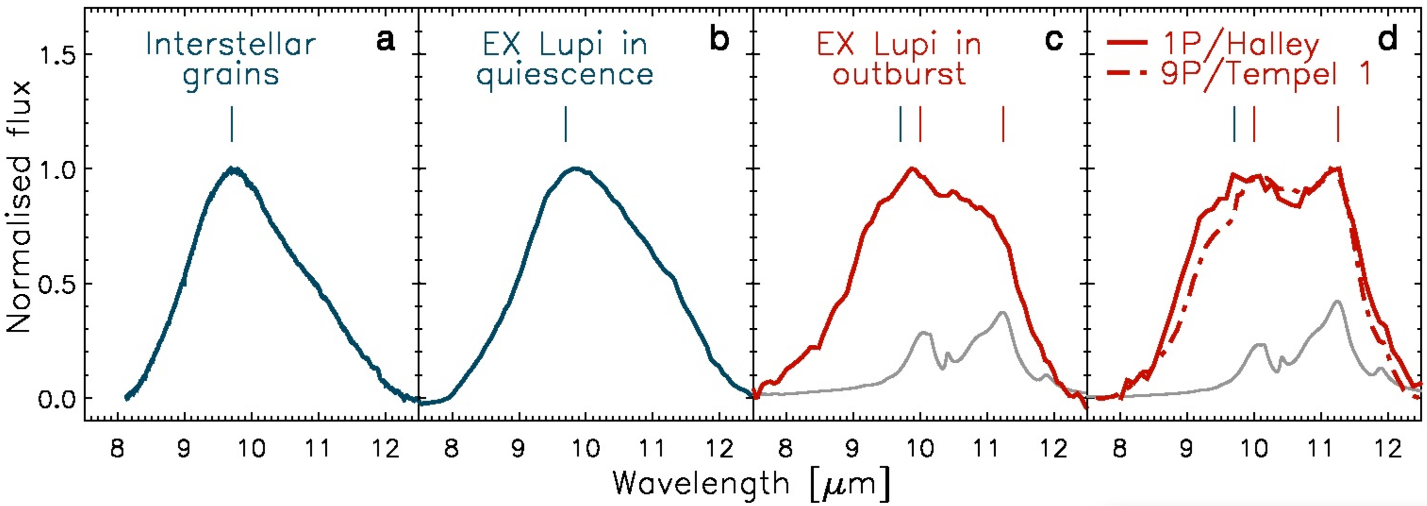
Lee (2007): part CO gas evaporated during episodic accretion event is frozen onto grains and converted into CO_2; see also Kim et al. (2011), Visser & Bergin (2012), Vorobyov et al. (2013), Visser (2014) → CO, CO_2, N_2H^+, HCO^+ time tracers of outbursts



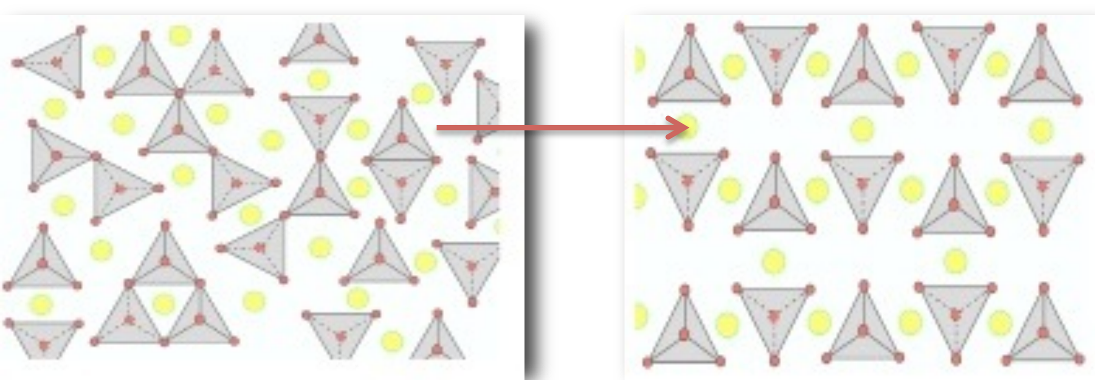
Vorobyov et al. (2013)

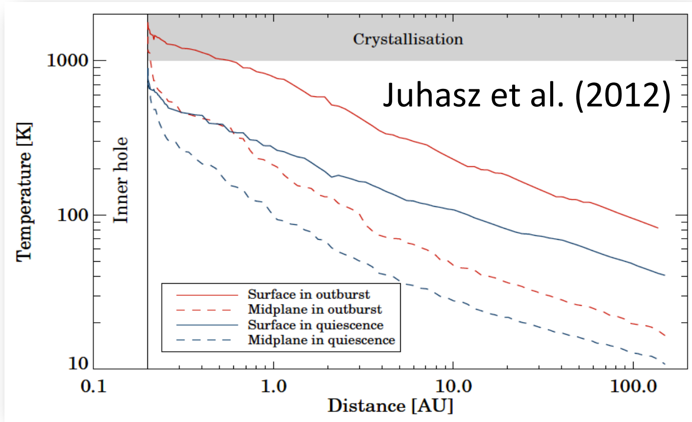
Silicate processing during outbursts

EX Lup outburst: evidence of silicate processing via flash heating above 1000 K (possibly also due to vertical transport and stirring of dust grains?). Unknown in FUors, yet to return to quiescence.

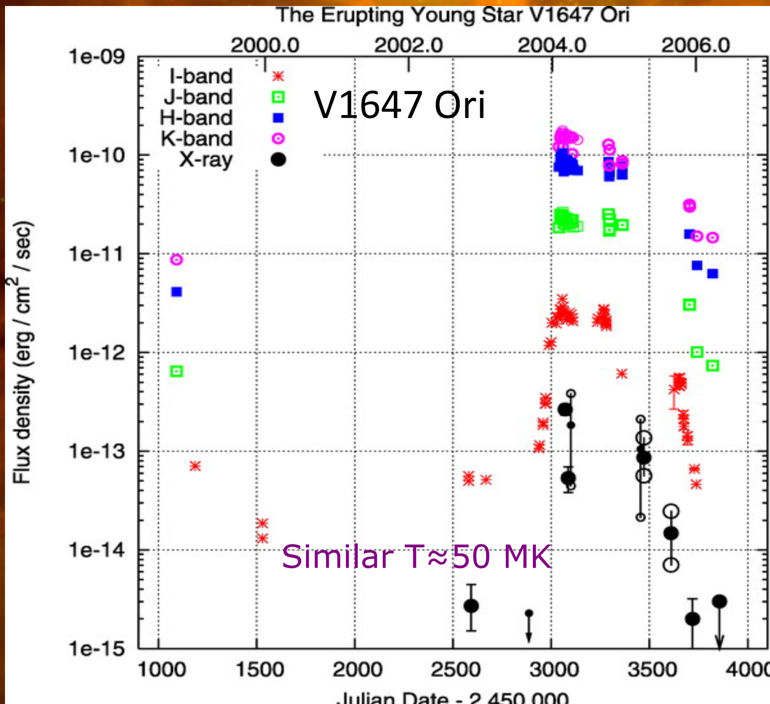


Ábraham et al.(2009)

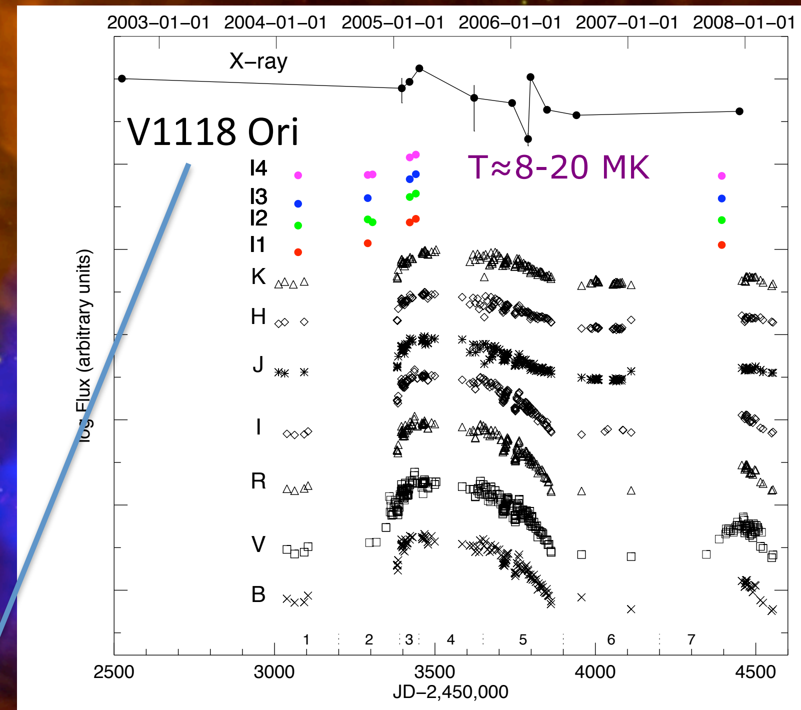




High-energy processes and episodic accretion



Kastner et al. (2006); Grosso et al. (2005); Hamaguchi et al. (2010, 2012)

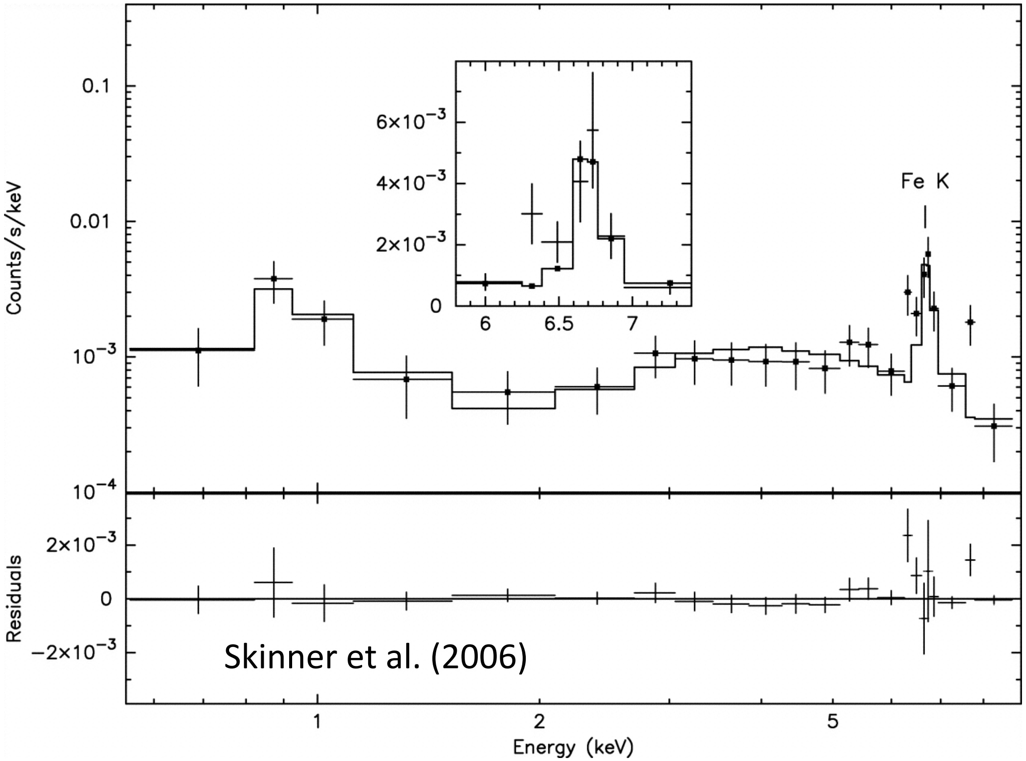


Audard et al. (2005, 2010), Lorenzetti et al. (2006) Grosso et al. (2010); Teets et al. (2012), EX Lup

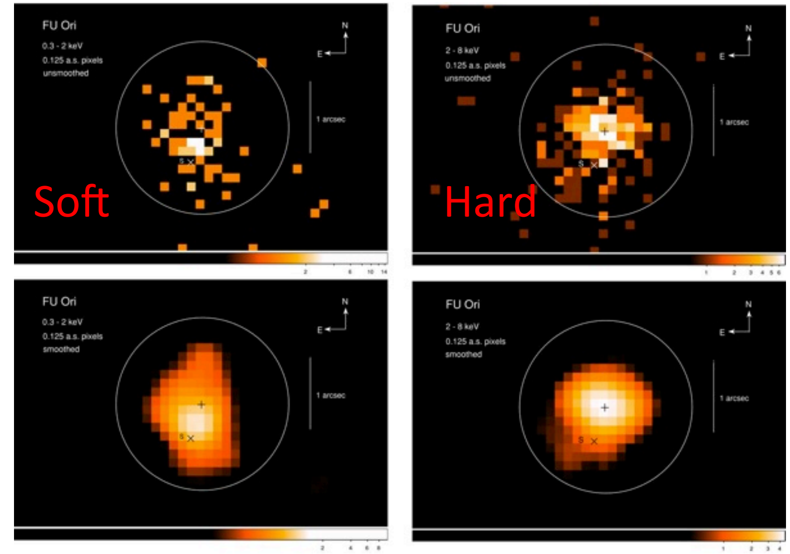
V1647 Ori: large flux increase, V1118 Ori/EX Lup: small increase

V1647 Ori: hot plasma and hardening; cool plasma present as well ; V1118 Ori: cooler plasma, possibly showing a decrease in T at the beginning of the outburst. N_H lower in V1118 Ori than V1647 Ori. EX Lup shows also decrease in cool plasma component

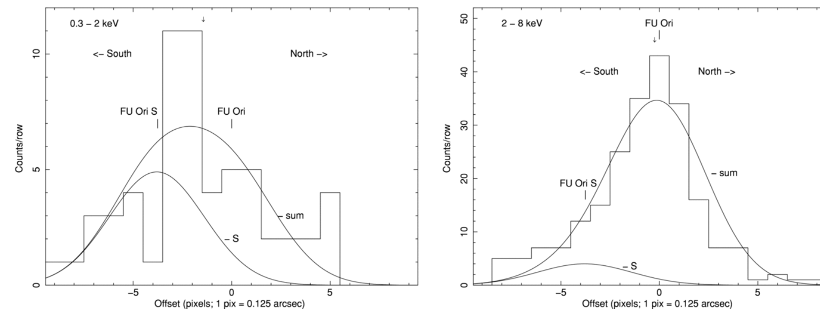
The very hot plasma of FU Ori



Skinner et al. (2006)



Skinner et al. (2010)



Cool and hot (>5 keV) plasma with different N_H: cool N_H consistent with A_V, 10x higher N_H ($\approx 10^{23}$ cm^{-2}) for hotter component, likely due to cold accreting gas or near-neutral wind. Strong Fe with possible Fe I at 6.4 keV.

New Chandra observation confirms 2-T plasma with dominating, variable hot plasma centered on FU Ori. Soft X-rays offset by 0.2” SE of FU Ori, toward FU Ori S.

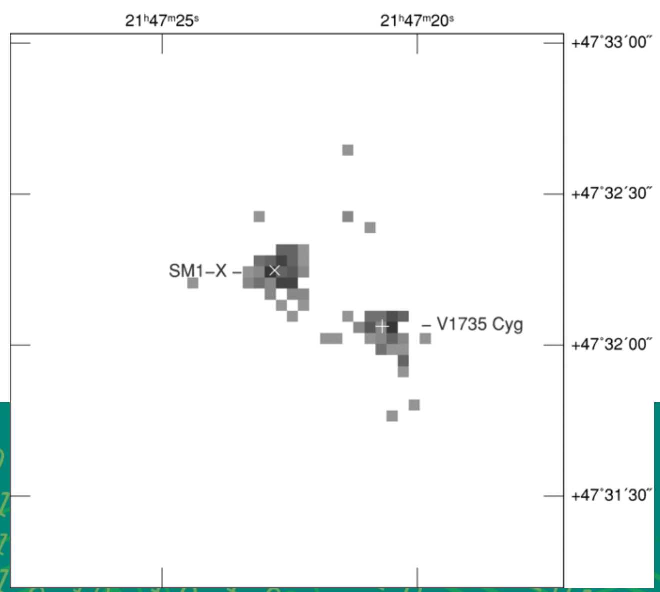
Cygnus objects

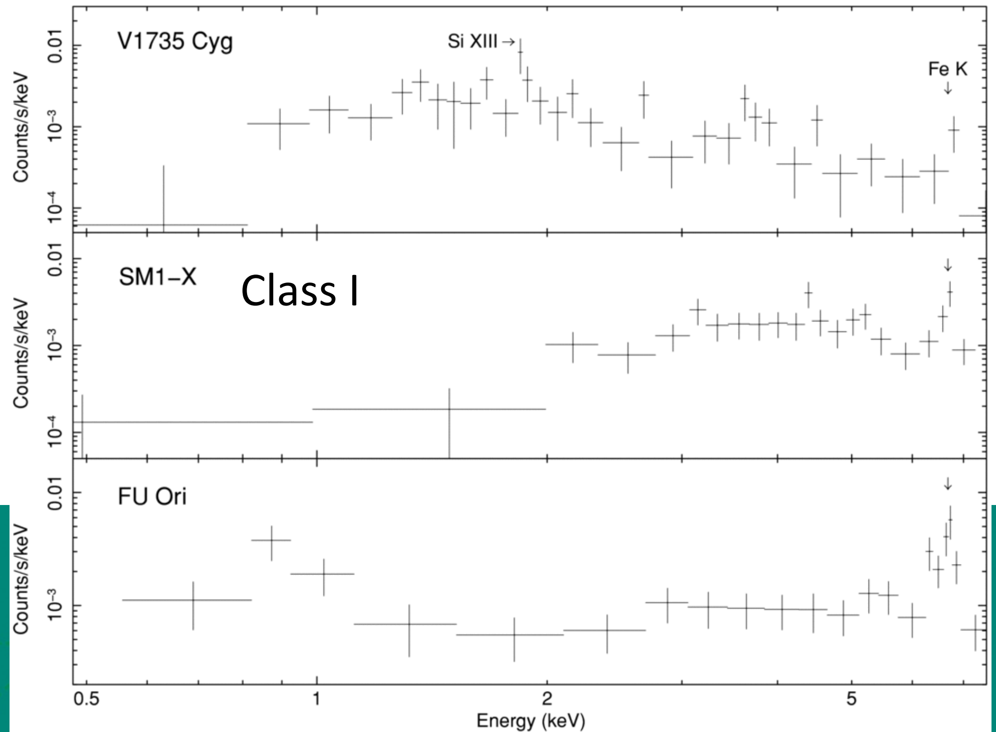
Skinner et al. (2009)

Table 3
Classical FUors

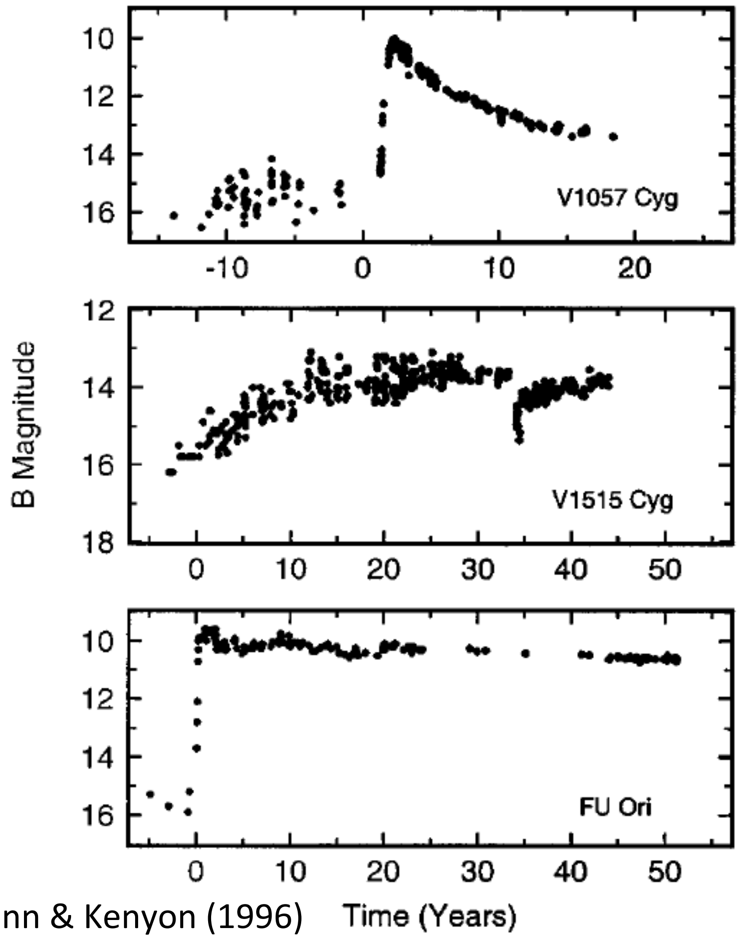
Star	Distance (pc)	A_V (mag)	L_{bol} ($L_\odot$)	log L_X (erg s^{-1})	Refs.
FU Ori	460	1.5–2.6	340–500	30.8 ± 0.4	1,2,3,4,5,6,7,8
V1735 Cyg	950–1200	8.0–10.8	235	31.0 ± 0.2	7,9,10,11
V1057 Cyg	600	3.0–4.2	250–800	$\leqslant 30.0^a$	1,2,3,7,12,13,14,15
V1515 Cyg	1000	2.8–3.2	200	$\leqslant 30.5^b$	1,2,7,8,13,14,15,16

Notes. L_{bol} refers to the star+disk system and includes IR-excess emission. L_X (0.5–7 keV) is unabsorbed and the uncertainties in L_X reflect the range of values obtained for different emission models (Table 2; SBG06). Upper limits on unabsorbed L_X are from the Portable Interactive Mult-Mission Simulator (PIMMS) using EPIC pn count rates in the 0.5–7 keV range inside an extraction circle of radius $R_e = 15''$ centered on the optical position.

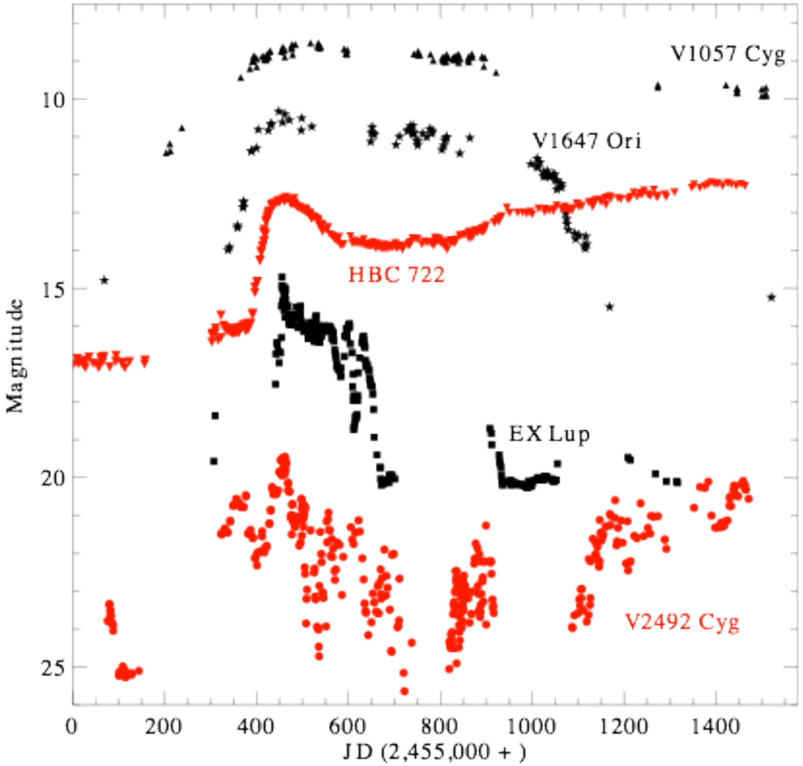




New outbursts : new timescales



Hartmann & Kenyon (1996)



Kóspál et al. (2011)

Timescale "blurring the lines"

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Further “issues” with the classification

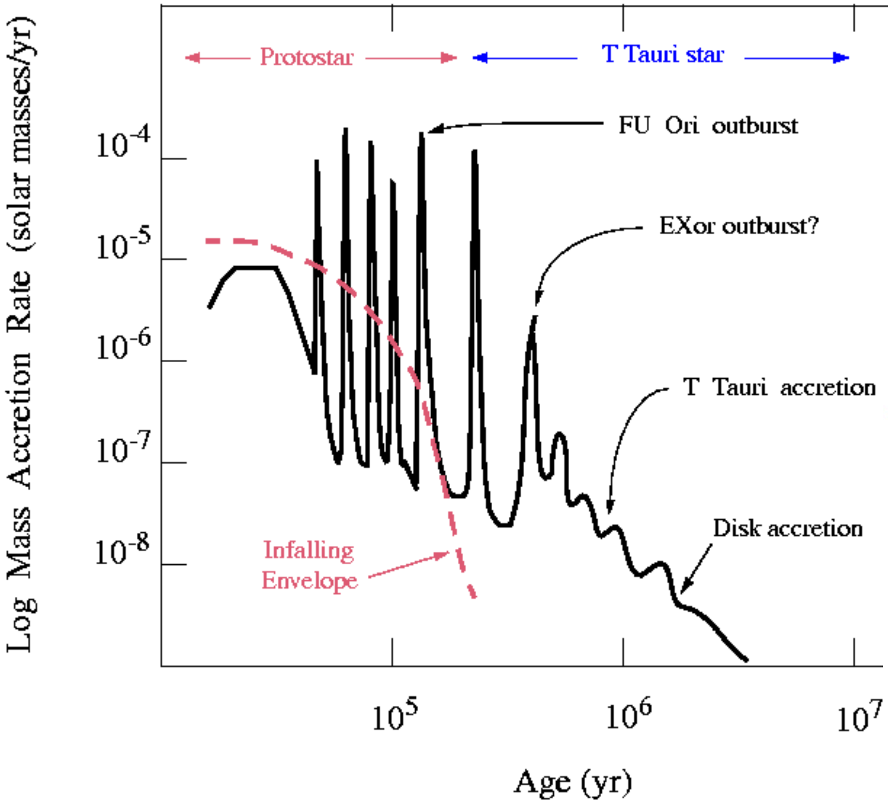
- Low-luminosity objects with “intermediate” luminosities (e.g., HBC 722, V2775 Ori, L_{bol}=10-50 L_{sun} in outburst)
- Embedded objects with EXor outburst characteristics (e.g., V723 Car, V1647 Ori, V2492 Cyg)

→ Conclusion may be that there is a continuum of properties of eruptive young stars and one should consider going away from the classical FUor/Exor approach (Audard et al. 2014)

The importance of eruptive young stars

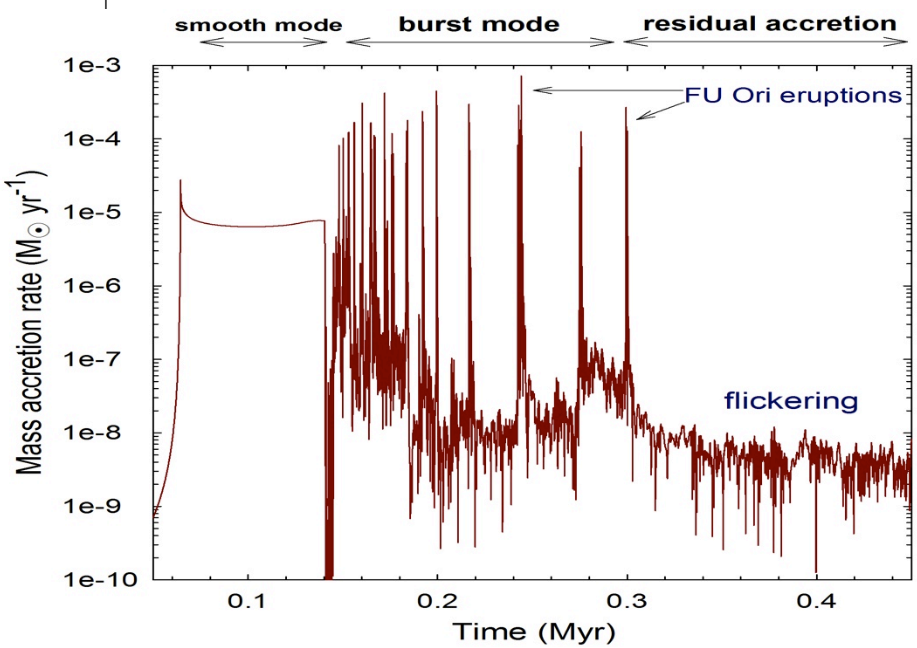
- FUors represent evolutionary stages during which most of the mass is expected to be accumulated
- Accretion mechanism(s) may differ from the classical magnetospheric TTS accretion model
- Offer "unveiled" examples of YSOs with accretion rates comparable to embedded sources
- They may solve some historic problems in star formation, such as the "luminosity problem" of protostars

From paradigm to models



Hartmann (1998)

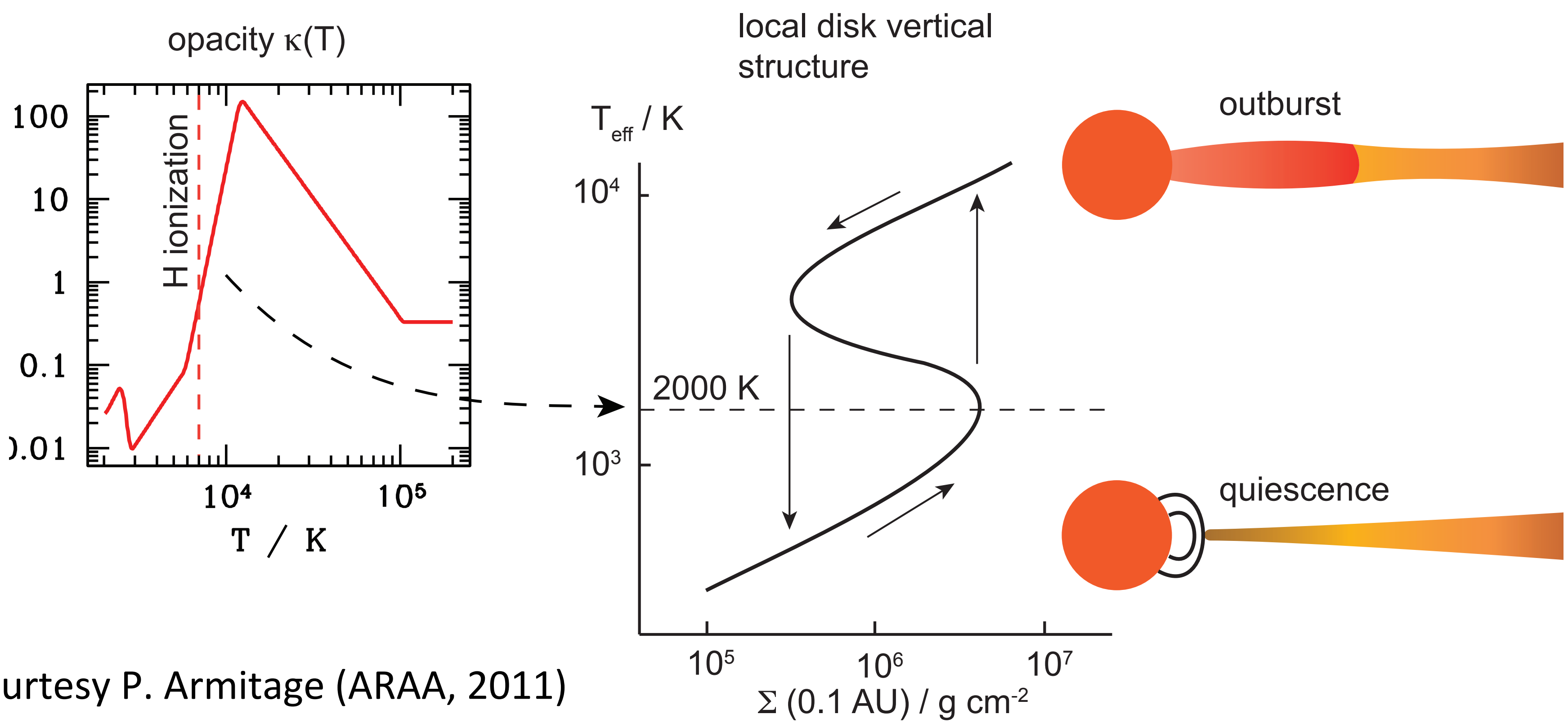
From disk fragmentation model of Vorobyov & Basu (2010)



Outburst mechanisms

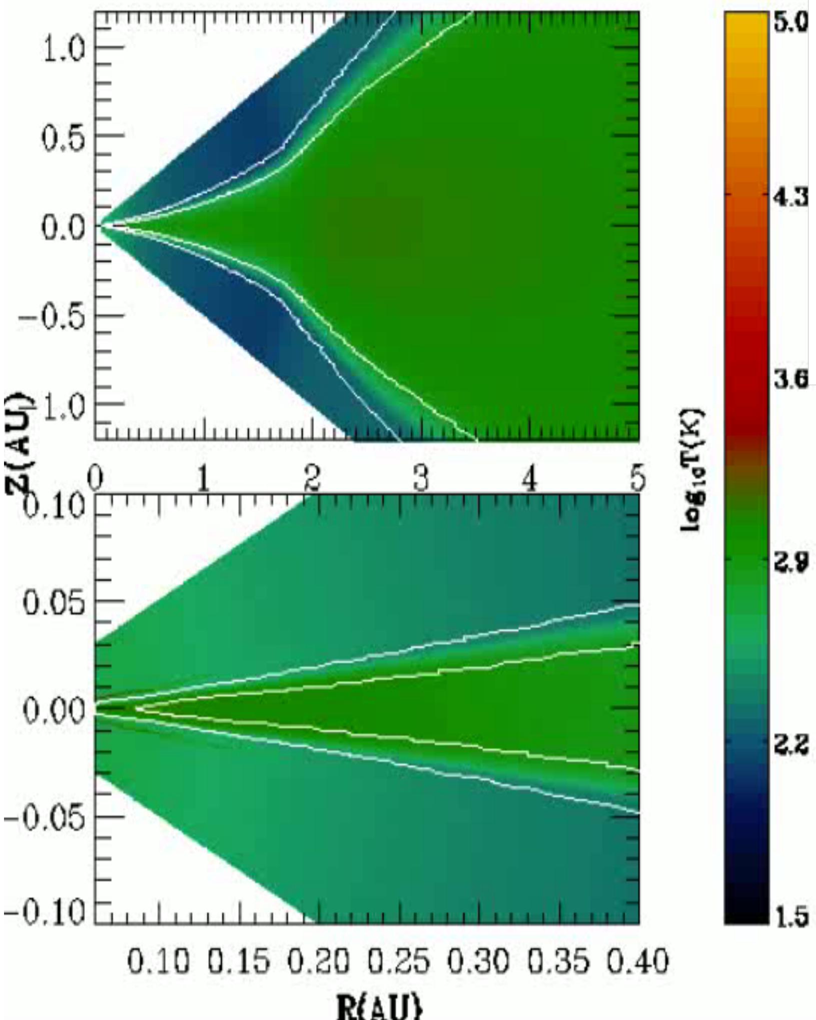
- Thermal instability (self-regulated and induced by planet)
  - Clarke et al. 1989; Bell+ 1994, 1995; Lodato & Clarke 2004, etc
- Gravitational instability in a massive disk, incl. magnetorotational instability
  - Armitage et al. 2001; Zhu et al. 2009, 2010, etc
- Disk fragmentation
  - Vorobyov & Basu (2006, 2010)
- Tidal interaction with a companion/nearby star
  - Bonnell & Bastian 1992, Reipurth & Aspin 2004; Pfalzner et al. (2008), etc
- Disk-magnetosphere interactions (mainly EXor events?)
  - Romanova et al. (2009); Kurosawa & Romanova (2012); Königl et al. (2011); D'Angelo & Spruit (2012)

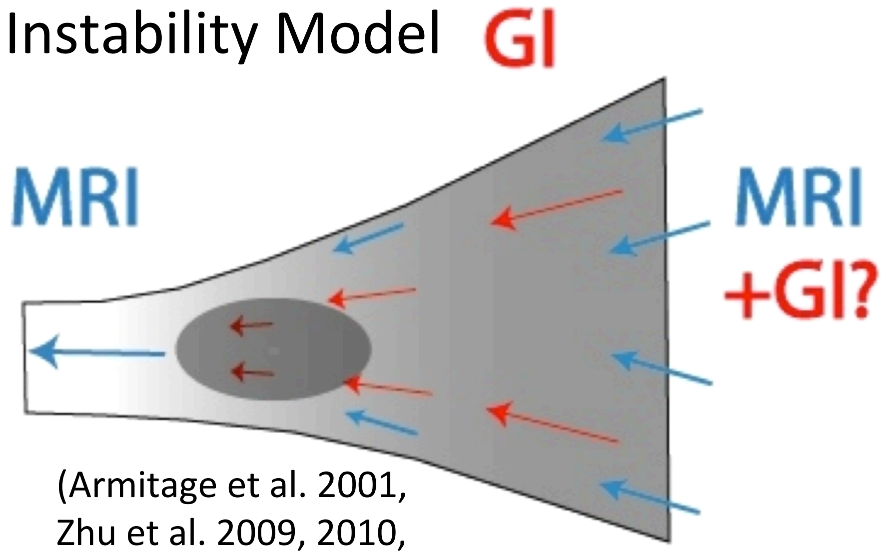
Thermal instability



Courtesy P. Armitage (ARAA, 2011)

Magnetorotational + Gravitational Instability Model (MRI+GI)





(Armitage et al. 2001,
Zhu et al. 2009, 2010,
Martin & Lubow 2011, Martin et al. 2012,
Bae et al. 2013)

GI: Outer Disk: Toomre criterion $Q=c_s\kappa/(\pi G\Sigma) \approx c_s\Omega/(\pi G\Sigma)\leq 1$

MRI: Inner Disk (hot/ionized)

Transition region: matter piles up at (1-10 AU) GI-MRI junction not smooth => episodic accretion

Predicts correct outburst strength and timescale

But the details of MRI triggering are uncertain

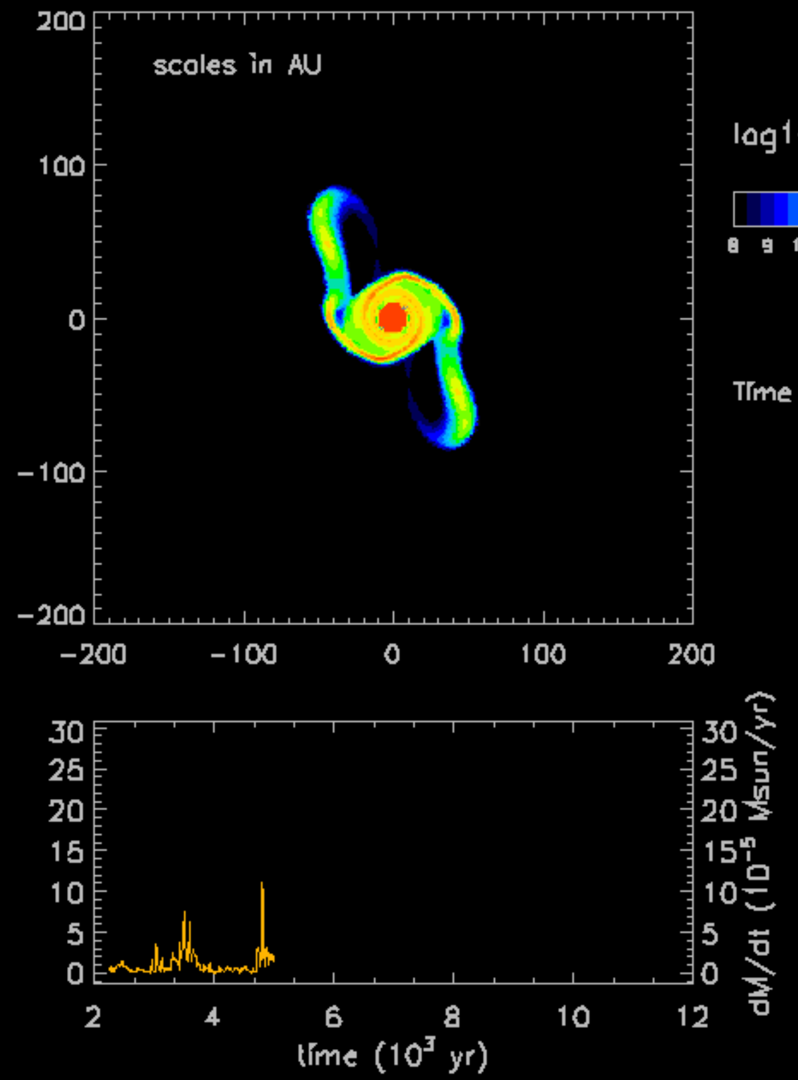
Zhu et al. 2009

Slide by Z. Zhu/J. Green, PPVI

Accretion bursts due to disk fragmentation in the embedded phase

If Toomre parameter $Q \leq 1.0$ and disk cooling is fast ($\Omega * t_c <$ a few), disk fragmentation can occur (e.g. Johnson & Gammie 2003, ApJ, 597, 131)

Initial core mass = 1.0 Msun



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
$10^{-5}\ M_{\odot}$ / year

Vorobyov & Basu 2006, ApJ, 650, 956
Vorobyov & Basu 2010, ApJ, 719, 1896
(see also Machida + 2011, ApJ, 729, 42)

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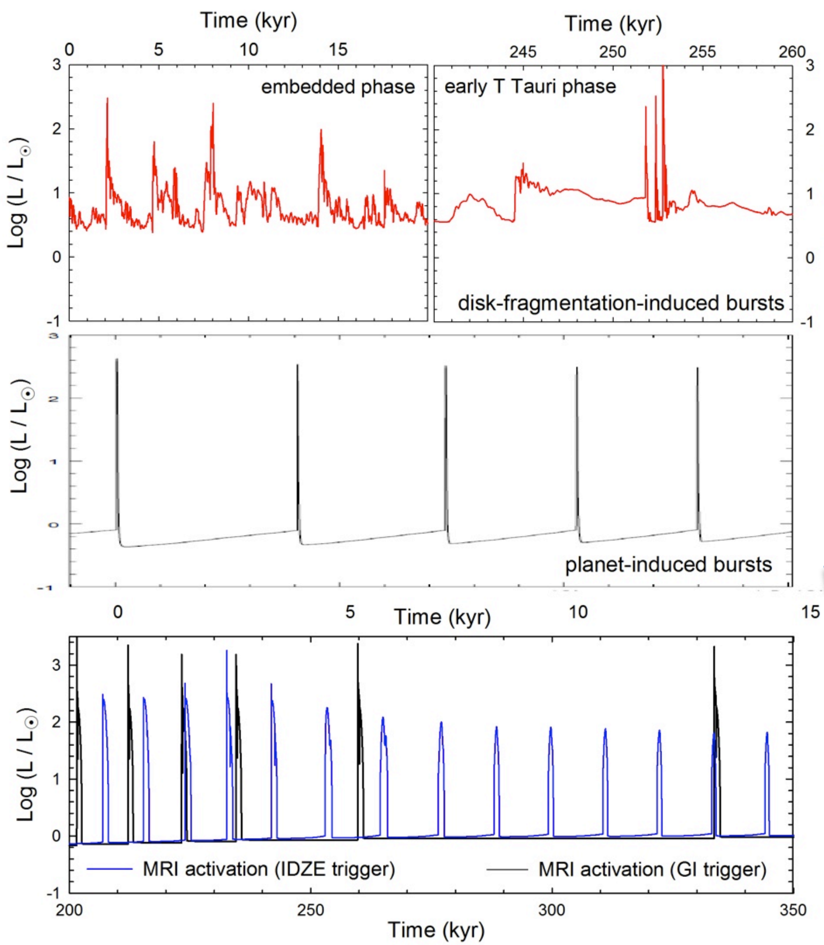
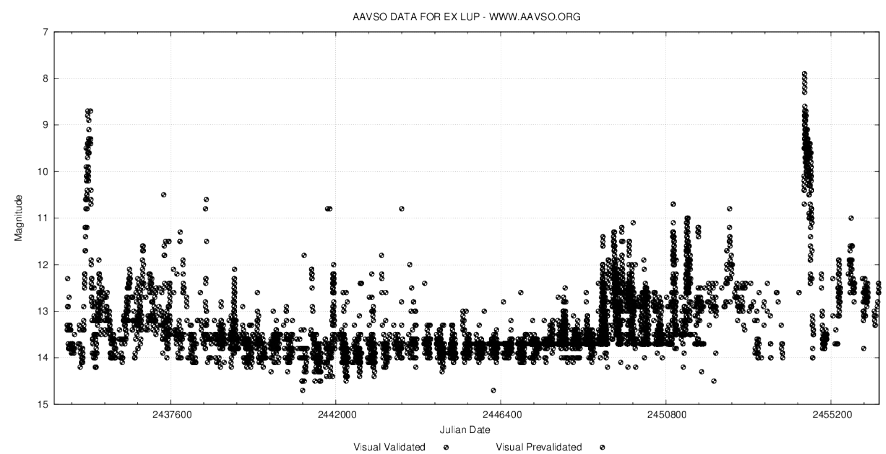
Modeled Outburst Frequency via Disk Instability





EX Lup (AAVSO; 1955-2010)

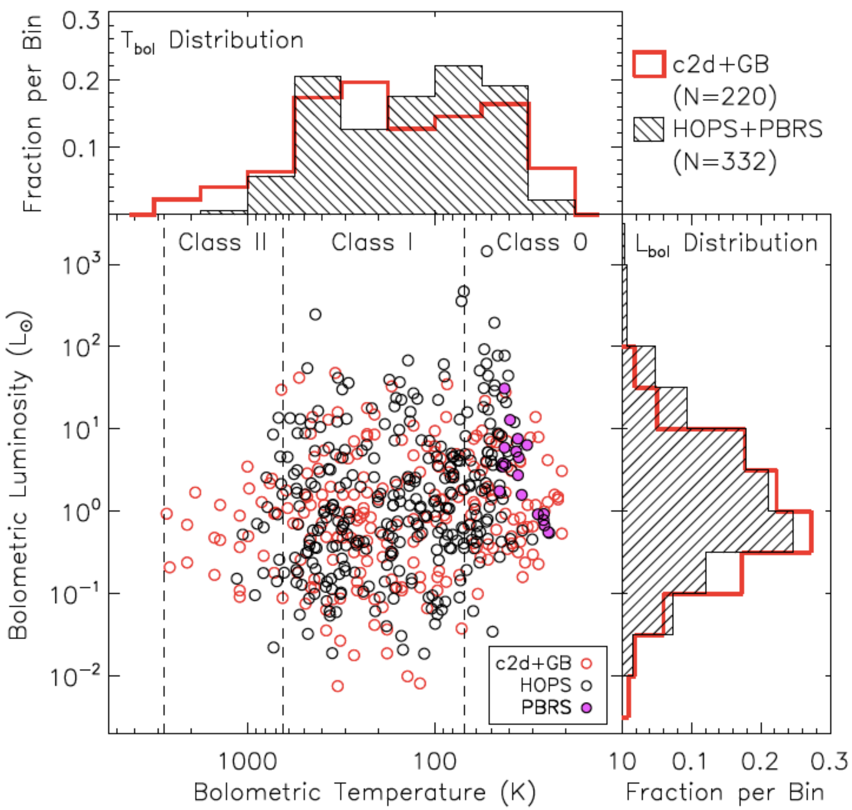
Vorobyov, 2013, A&A, 552, 129

Or binary companion?

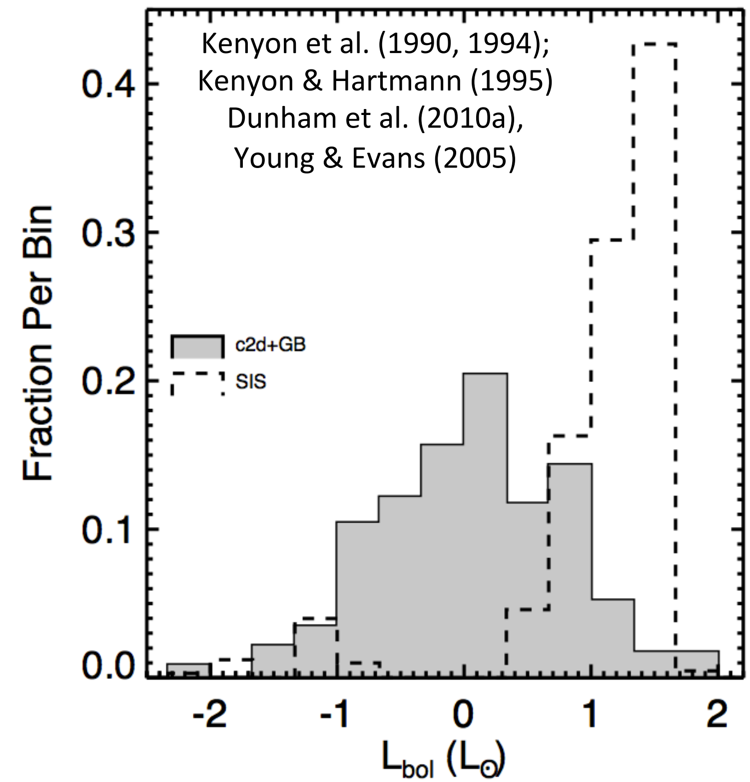
The protostellar luminosity problem

Kenyon et al. (1990, 1994)

Dunham et al. (2014)



Models of single isothermal sphere with rotation

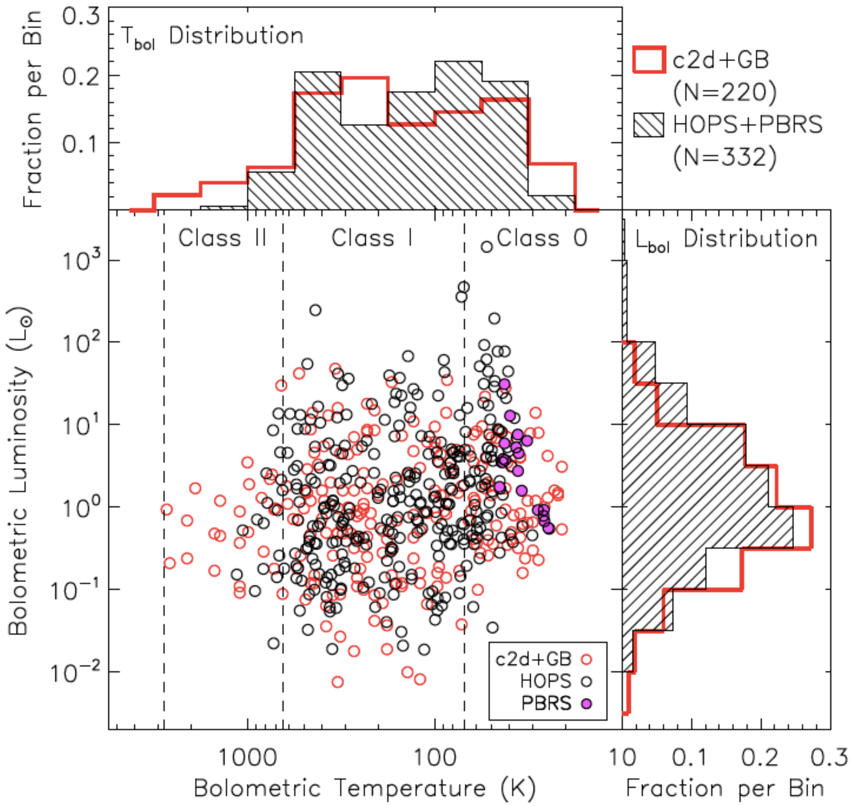


$$L = L_* + L_{acc} = \frac{3}{7}\frac{GM_*^2}{R_* t_{KH}} + \frac{GM_*\dot{M}}{2R_*} = L_*\left(1 + \frac{7}{6}\frac{t_{KH}}{t_{acc}}\right)$$

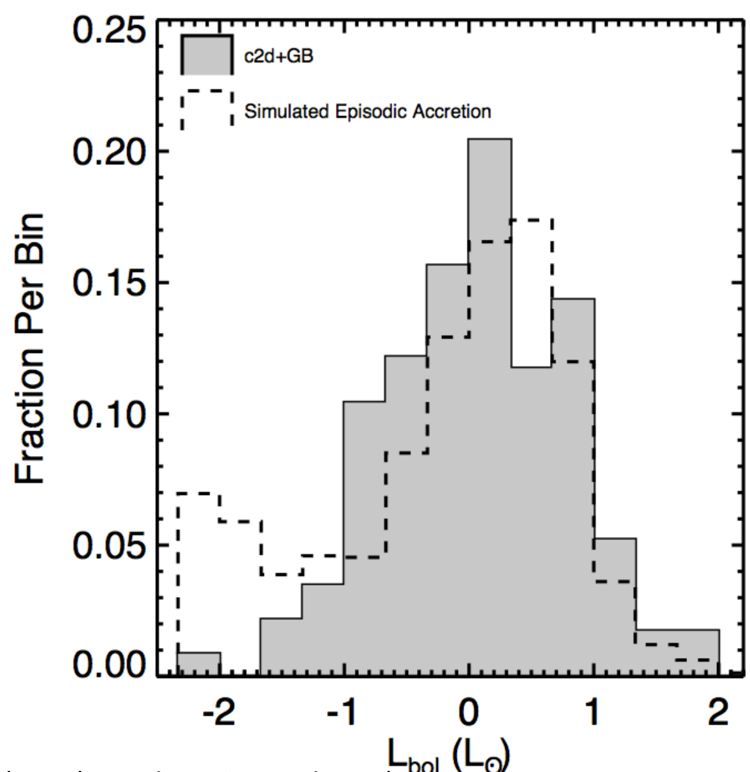
$t_{KH} > t_{acc}$ in protostars → L(protostar)>L(T Tau star) for same mass, in theory

The protostellar luminosity problem

Dunham et al. (2014)



Models with simulated episodic accretion



Dunham et al. (2010), Dunham & Vorobyov (2012)

Consequences of episodic accretion

- Padoan et al. (2014) suggest that episodic accretion is in fact not necessary to explain the luminosity problem if one takes into account external accretion (historic infall rates) into the modeling of the luminosity …
- Episodic accretion may explain luminosity spread in young clusters (Baraffe et al. 2009, 2012)
- Conditions for planet formation may depend on last episode of disk instability (e.g., Stamatellos et al. 2011, 2012; Vorobyov 2013)

Conclusions

- Episodic accretion appears to move from a "special case" to a more common event in the life of young stars
- The distinction between classes of FUors and EXors is being blurred with intermediate cases
- The timescale remains the primary distinction
- However, it remains unclear if the mechanisms at the origin of the outbursts are the same or distinct (or a combination)
- Models mimic well the outburst properties, but it remains unclears of which mechanism is the dominant one

Future prospects

- Discovery of new objects via dedicated time and large-scale surveys (e.g., WISE, YSOVAR, DSS, PTF, LSST, Gaia, …) will help provide better statistics of episodic accretion and will provide new grounds to study in more details such objects
- ALMA/NOEMA will help us relate envelop and disk masses in FUors and EXors, study the disk kinematics, and the chemistry in disks/envelopes modified by episodic accretion events
- Further models are needed to investigate numerically the link between FUors and EXors by treating the inner and outer disk simultaneously

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