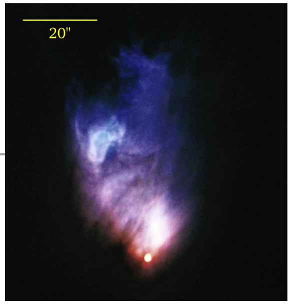
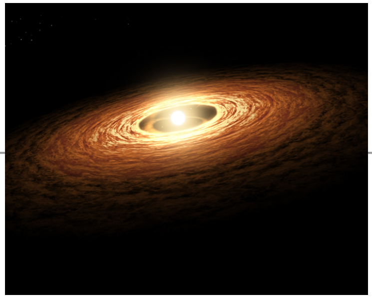
Episodic accretion phenomena in T Tauri stars





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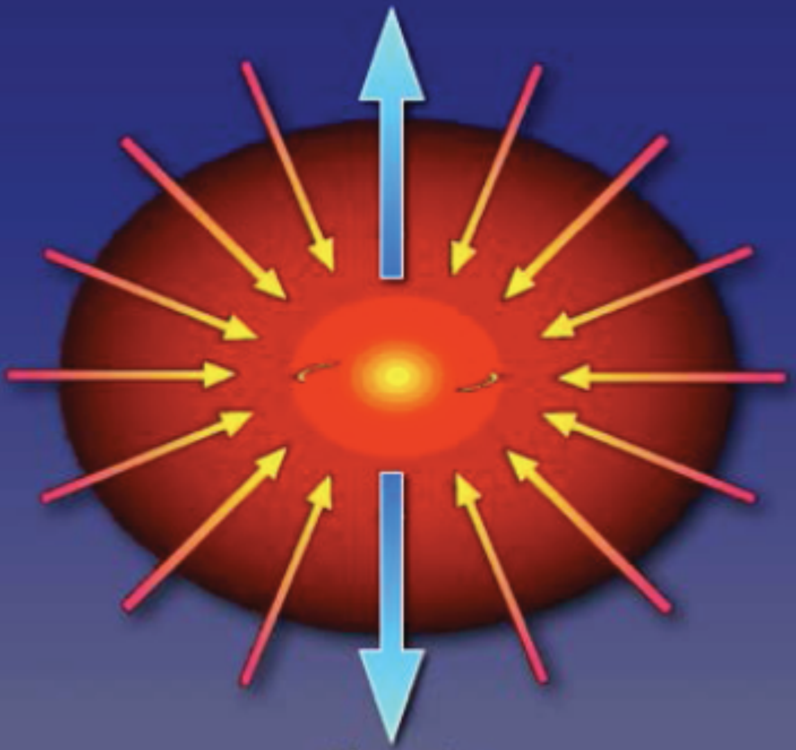
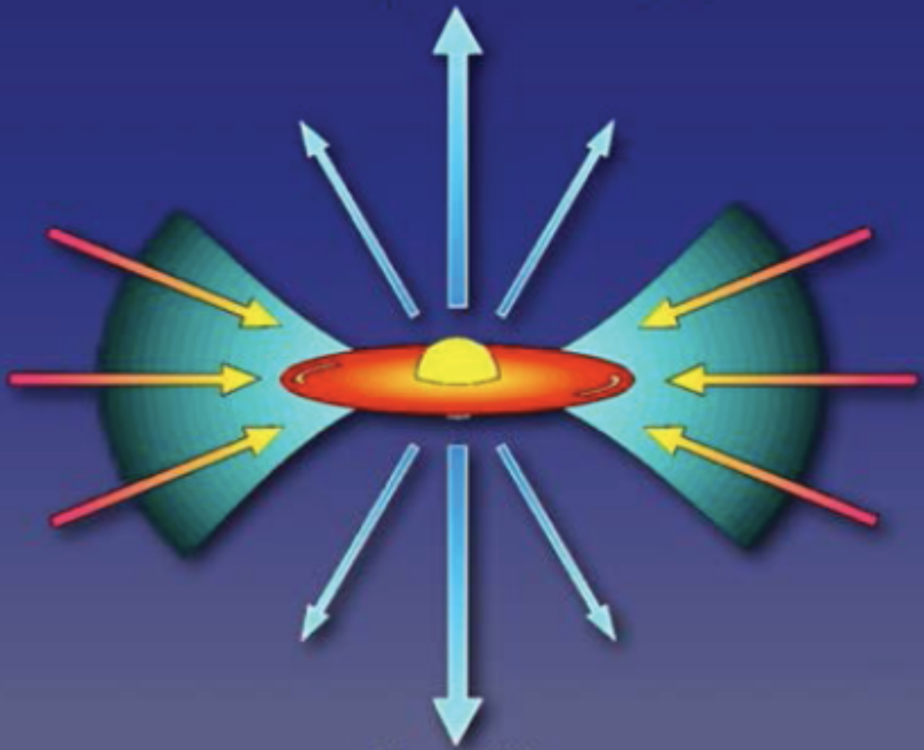
2017 October 25th

The isolated star formation paradigm



Class 0:
10^4 yrs; 10-10^4 AU; 10-300 K



Class I-II:
10^{5-6} yrs; 1-1000 AU; 100-3000 K

Class II-III:
10^{6-7} yrs; 1-100 AU; 100-5000 K

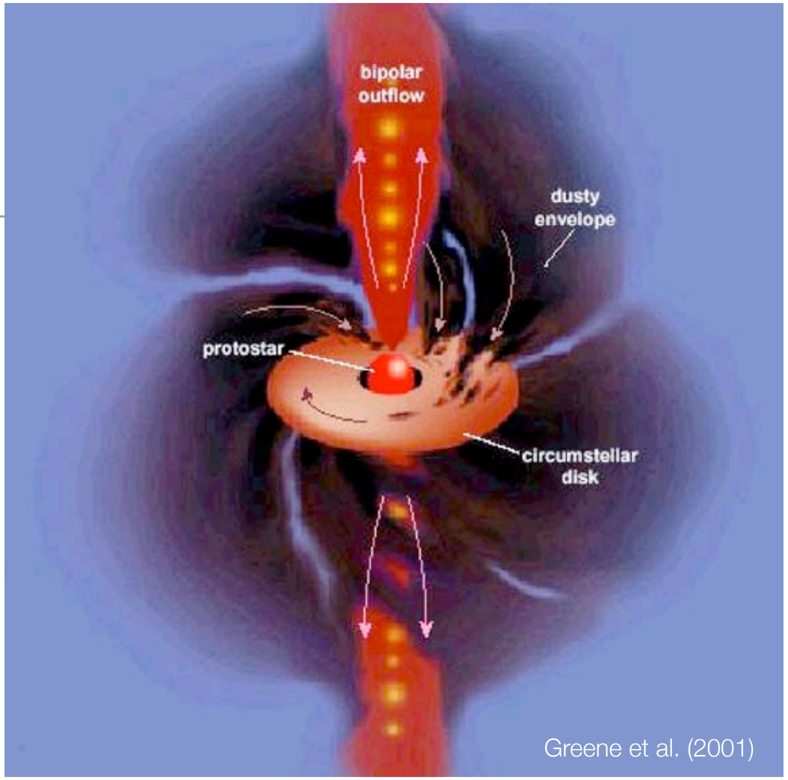
Class IV:
10^{7-9} yrs; 1-100 AU; 100-5000 K

Courtesy of Mark McCaughrean

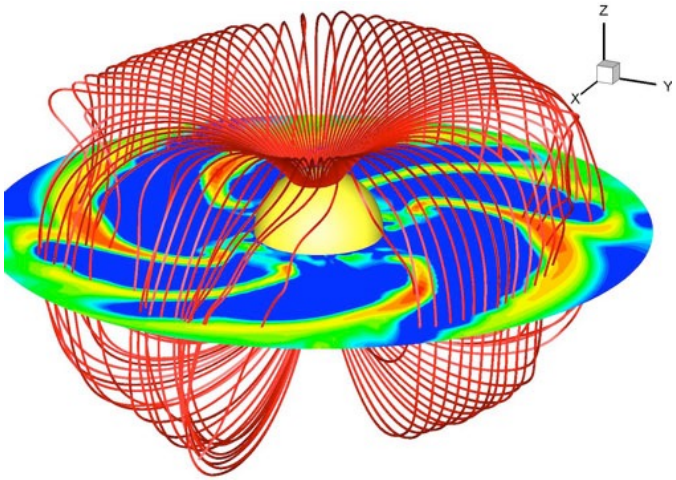
After Shu, Adams, & Lada

Mass accretion

- Interstellar gas and dust falls from the envelope onto the outer disk
- Matter gradually spirals inwards
- It accretes onto the stellar surface (equatorial plane? magnetic lines?)
- A fraction of the infalling matter in blown away in outflows



Greene et al. (2001)

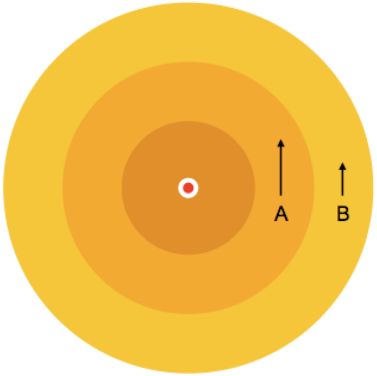


Credit: M. Romanova

- Accretion heats the disk directly (inner parts)
- Accretion increases the luminosity of the star (hot spot, UV radiation); the higher irradiation also heats the disk surface

Accretion: is it that easy?!

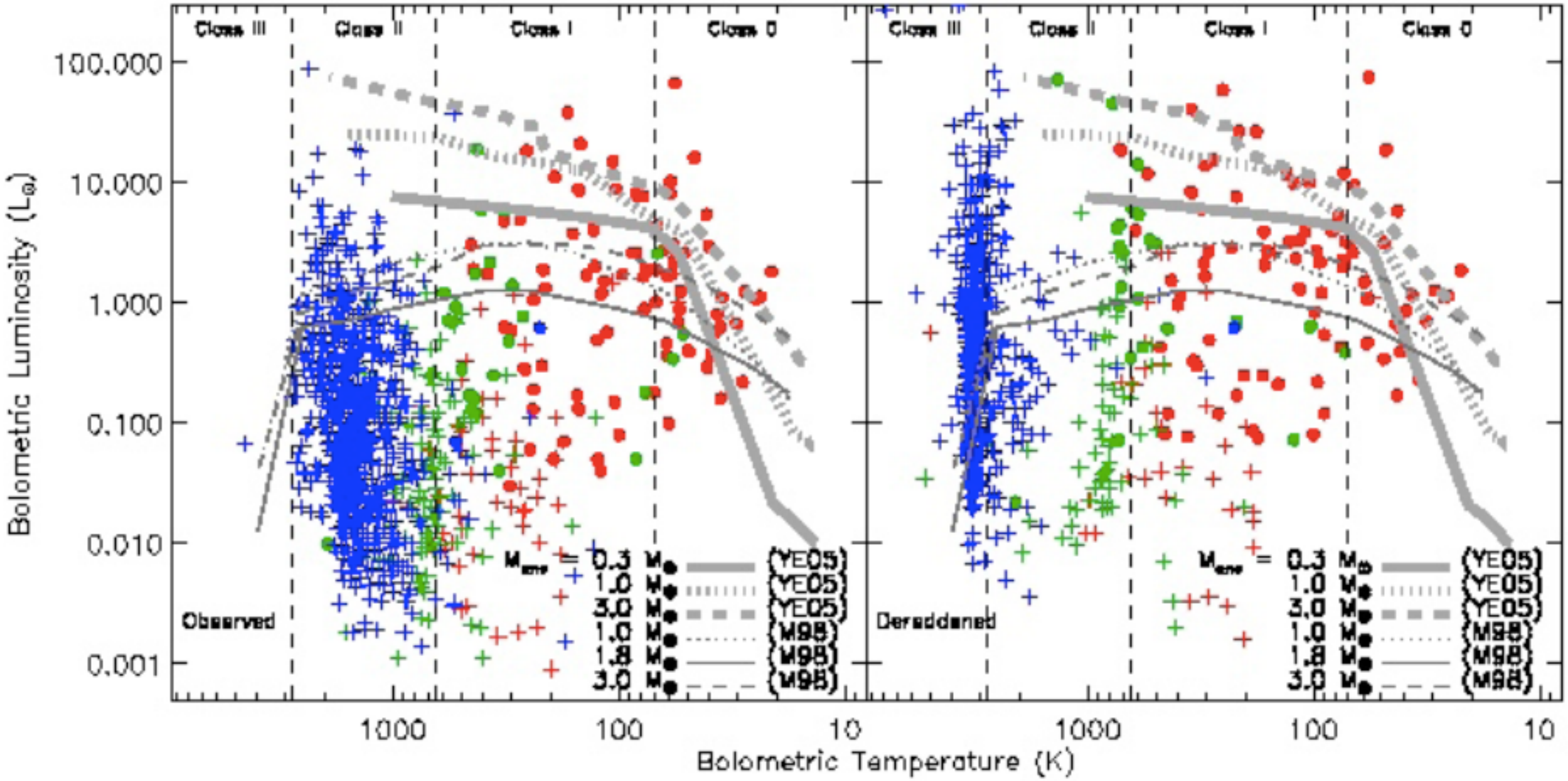
- Mass accretion is A VERY DIFFICULT PROCESS: angular momentum has to be removed
- Turbulence, viscosity
- Depends on local temperature (sound speed, local ionization degree)
- Angular momentum removal can be a bottleneck in the accretion process at certain disk radii



Credit: K. Dullemond

- It seems that mass accretion from envelope to disk is not a problem
- Accretion through the outer disk - no information
- Potentially big problems in the vicinity of the star!

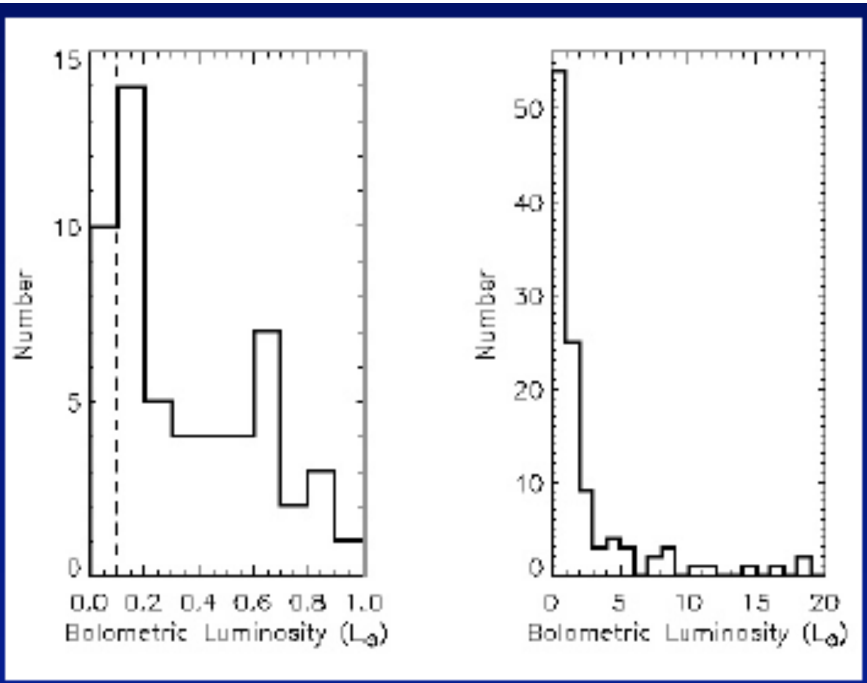
“Luminosity problem” -> Episodic accretion?



Evans et al. (2009)

- the luminosity of protostars is less than expected.

Luminosity of embedded sources

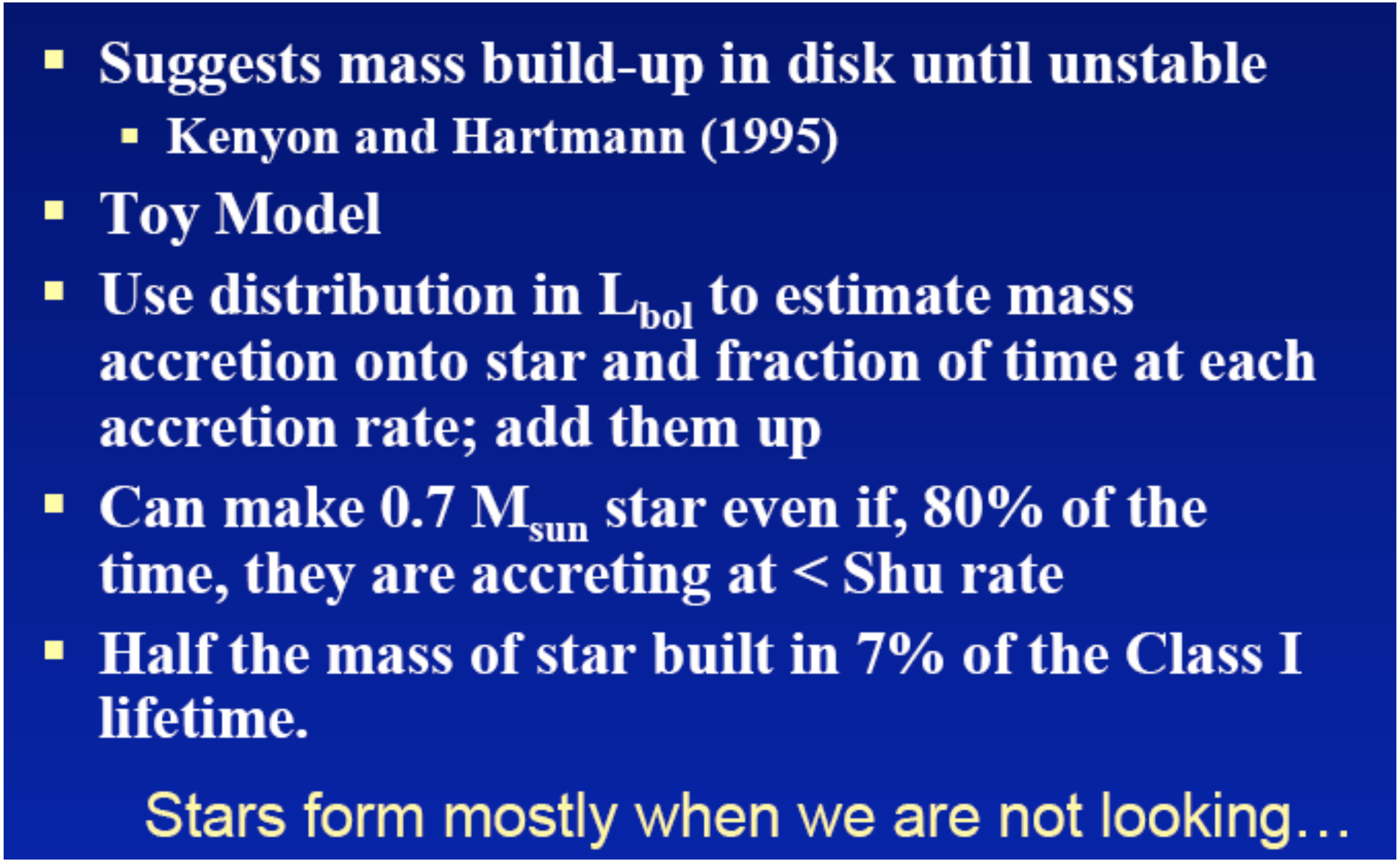


Histogram of luminosities of embedded (mm continuum) sources. Blow-up of $L < 1\ L_{sun}$ on left. Three sources off scale on right up to 70 L_{sun}. Predicted $L = GM(dM/dt)/R = 1.6\ L_{sun}$ for standard (Shu) accretion onto $M = 0.08\ M_{sun}$, $R = 3\ R_{sun}$. Most (59%) are below this. Corrections for extinction may increase L_{bol} by factor of two on average.

Points to episodic accretion.

Evans et al. (2009)

Episodic accretion



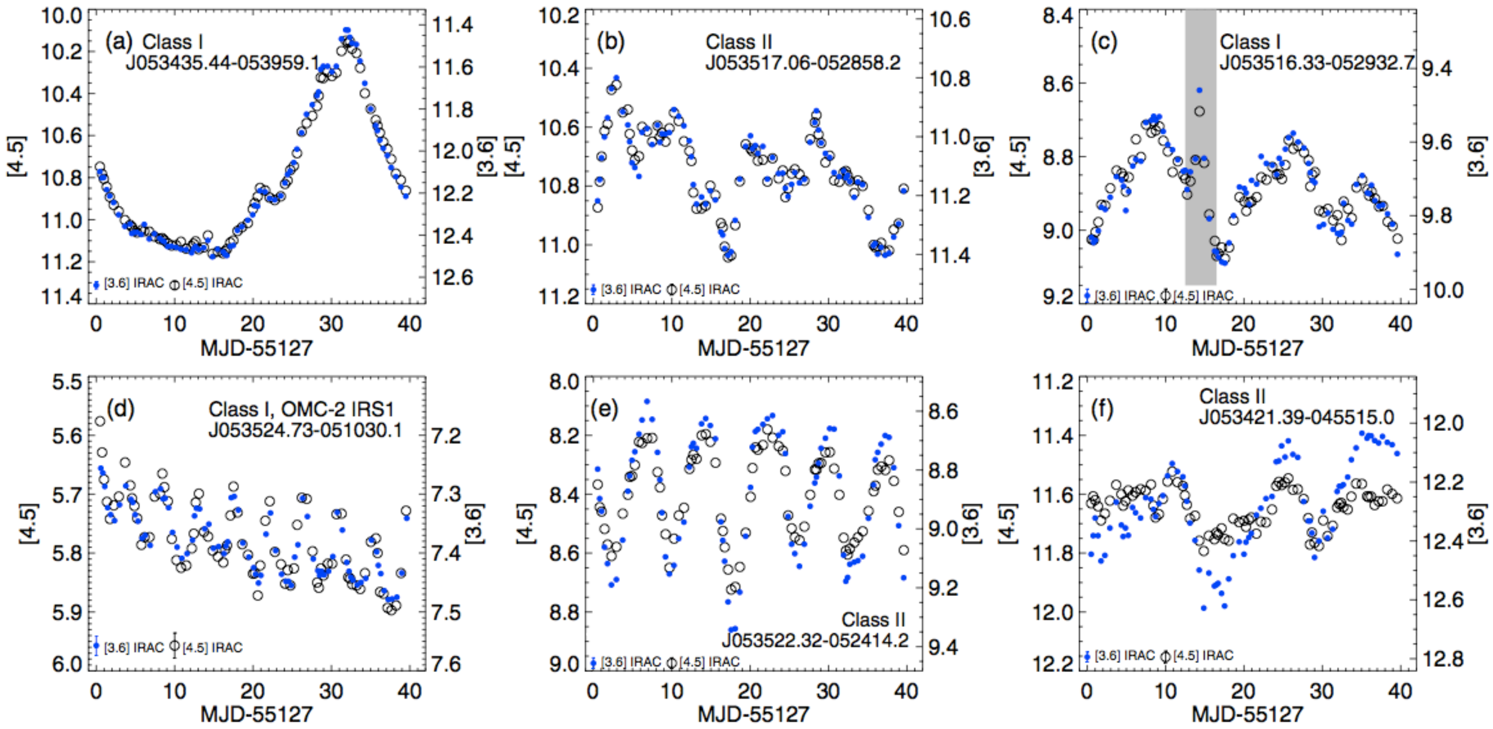
- Suggests mass build-up in disk until unstable
    - Kenyon and Hartmann (1995)
- Toy Model
- Use distribution in L_{bol} to estimate mass accretion onto star and fraction of time at each accretion rate; add them up
- Can make 0.7 M_{sun} star even if, 80% of the time, they are accreting at < Shu rate
- Half the mass of star built in 7% of the Class I lifetime.

Stars form mostly when we are not looking…

Evans et al. (2009)

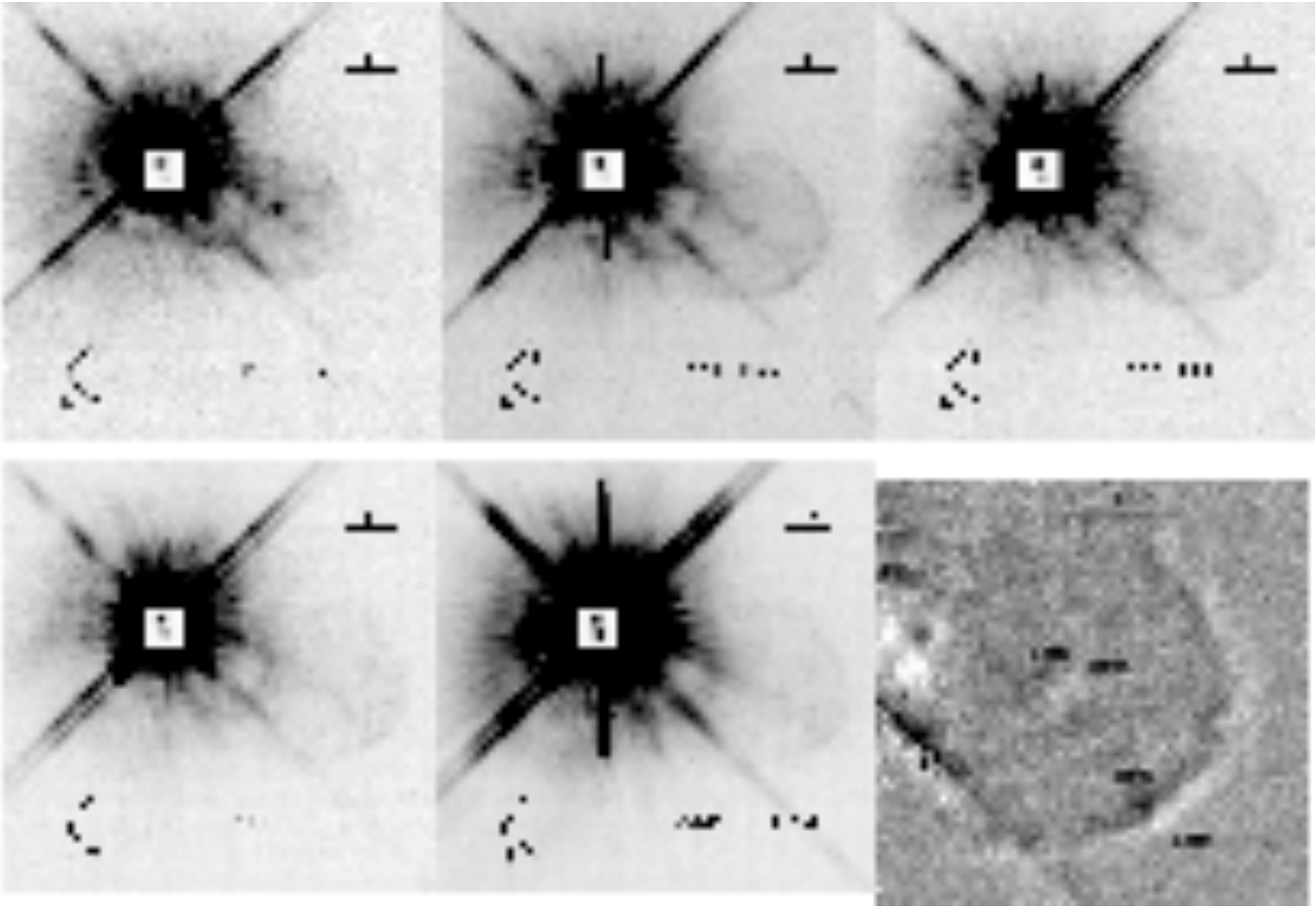
Smaller scale variability of young stars

- T Tauri stars are “by definition” variable objects (Joy, 1945)
- Main reasons of light changes: (1) cold stellar spots (like sunspots, but bigger); (2) passing dust clump in front of the star; and (3) **time variable accretion from the disk onto the star**.
- Timescale: as short as 1 week; Amplitude: 1-2 mag (2-5x)
- Probably NOT driven by an instability



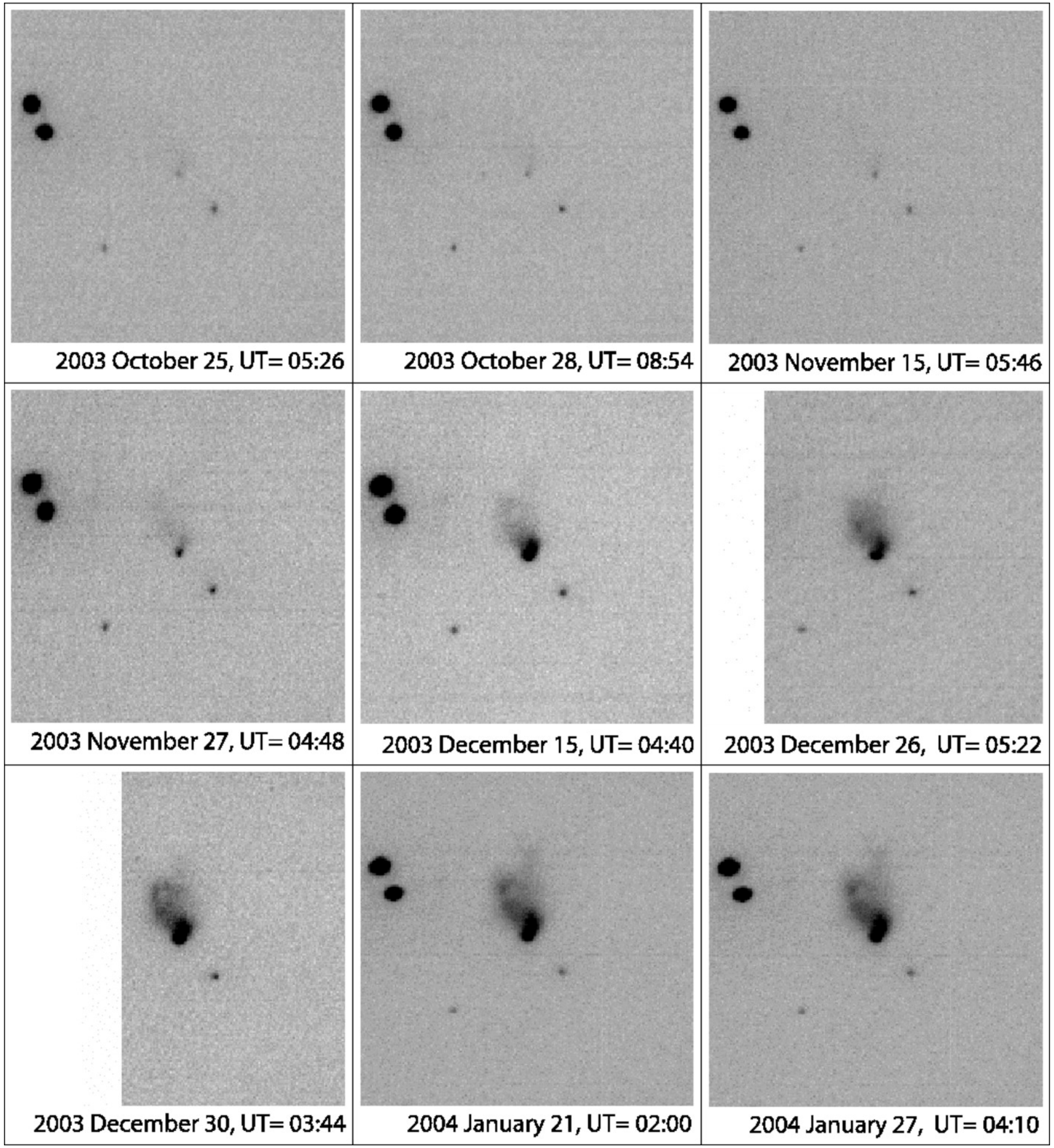
Morales-Calderón et al. 2011

The brightening of XZ Tau



Coffey et al. 2004

The brightening of V1647 Ori



2003 October 25, UT= 05:26

2003 October 28, UT= 08:54

2003 November 15, UT= 05:46

2003 November 27, UT= 04:48

2003 December 15, UT= 04:40

2003 December 26, UT= 05:22

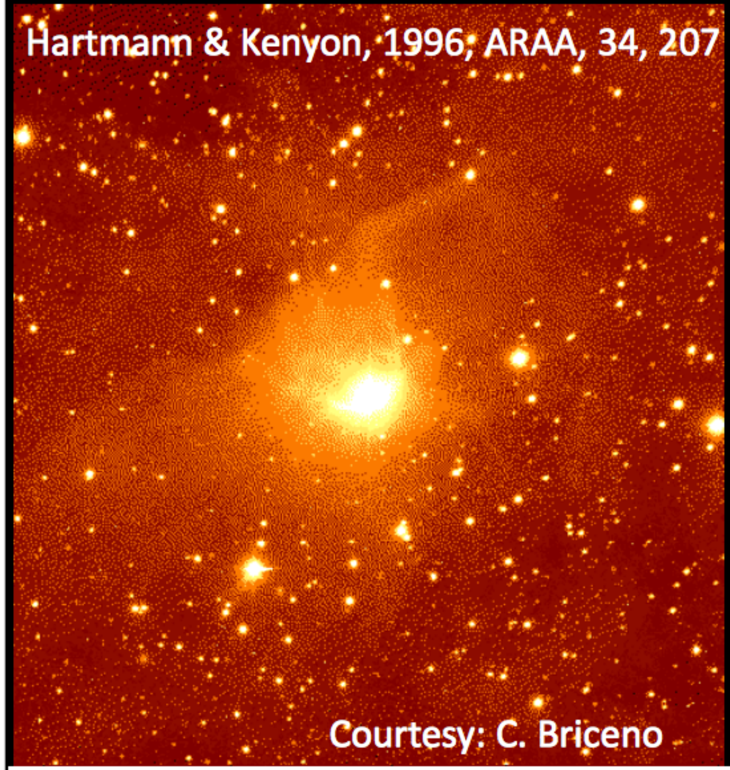
2003 December 30, UT= 03:44

2004 January 21, UT= 02:00

2004 January 27, UT= 04:10

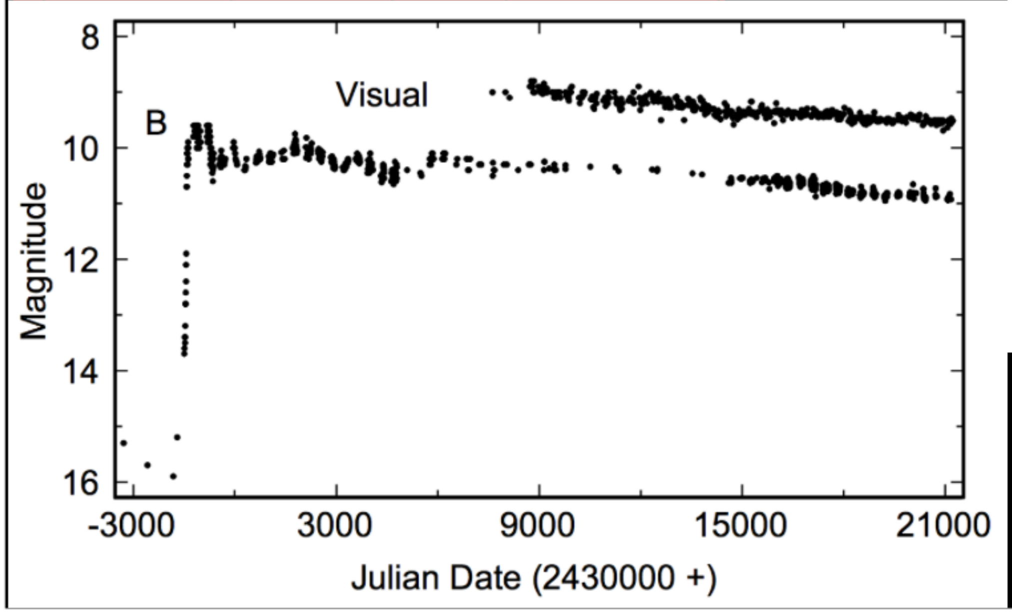
Briceno et al. 2004

The FU Orionis Eruption: 1936

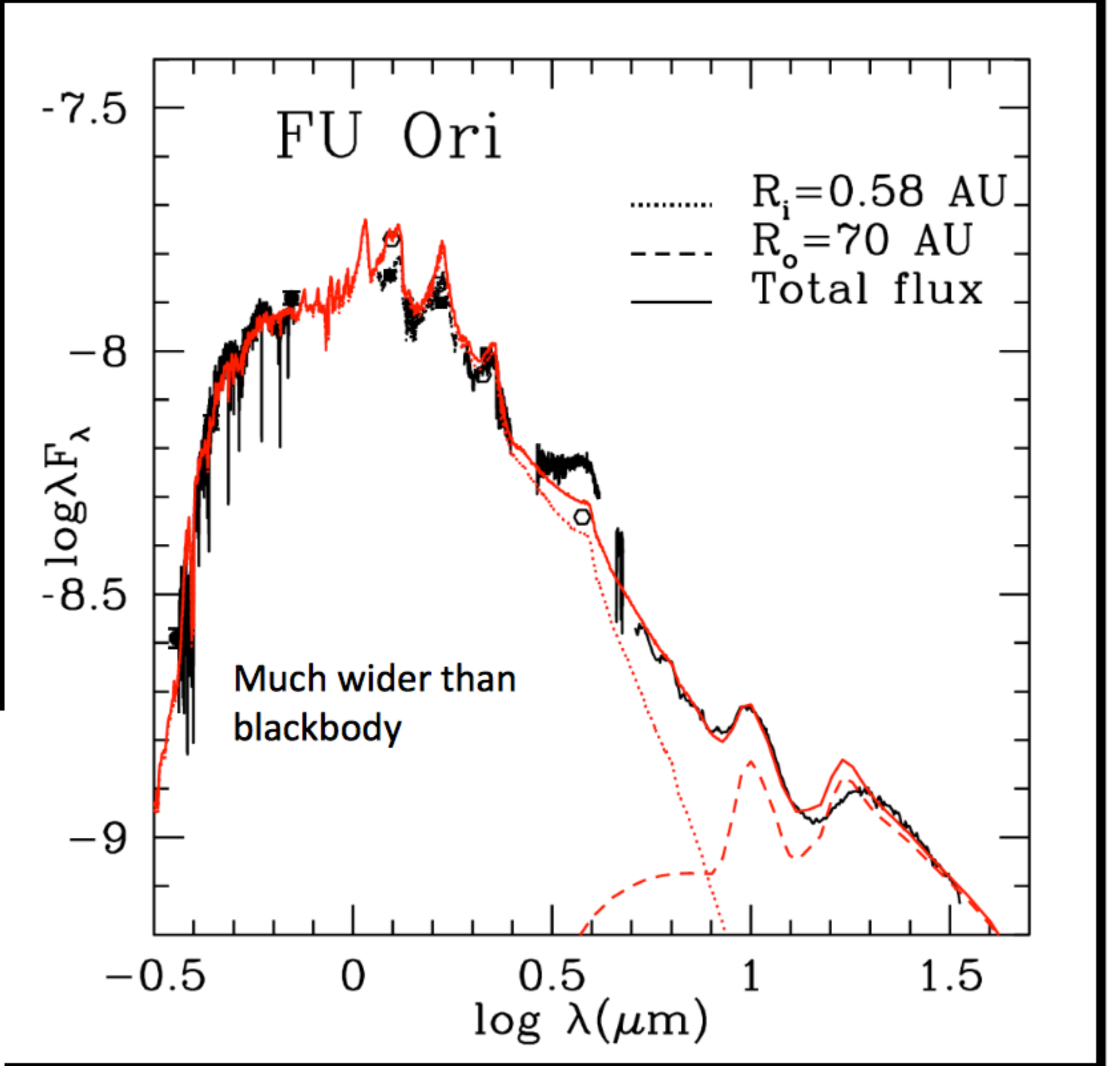


Hartmann & Kenyon, 1996; ARAA, 34, 207

Courtesy: C. Briceno



Kenyon et al. (2000, ApJ 531, 1028)

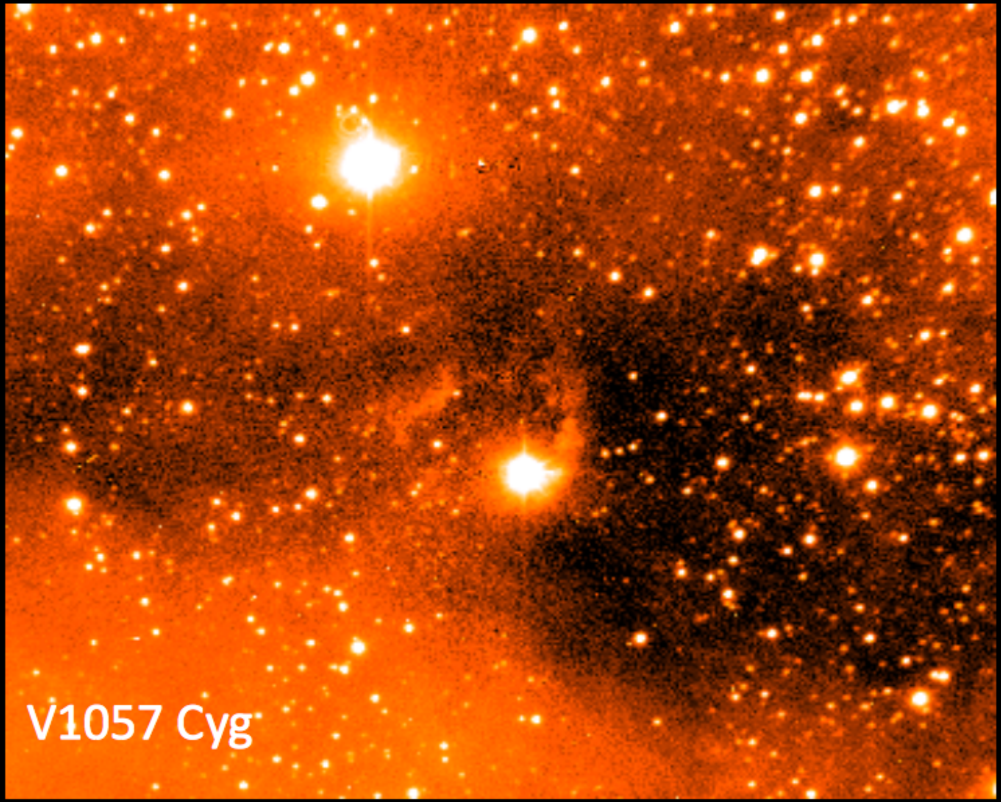


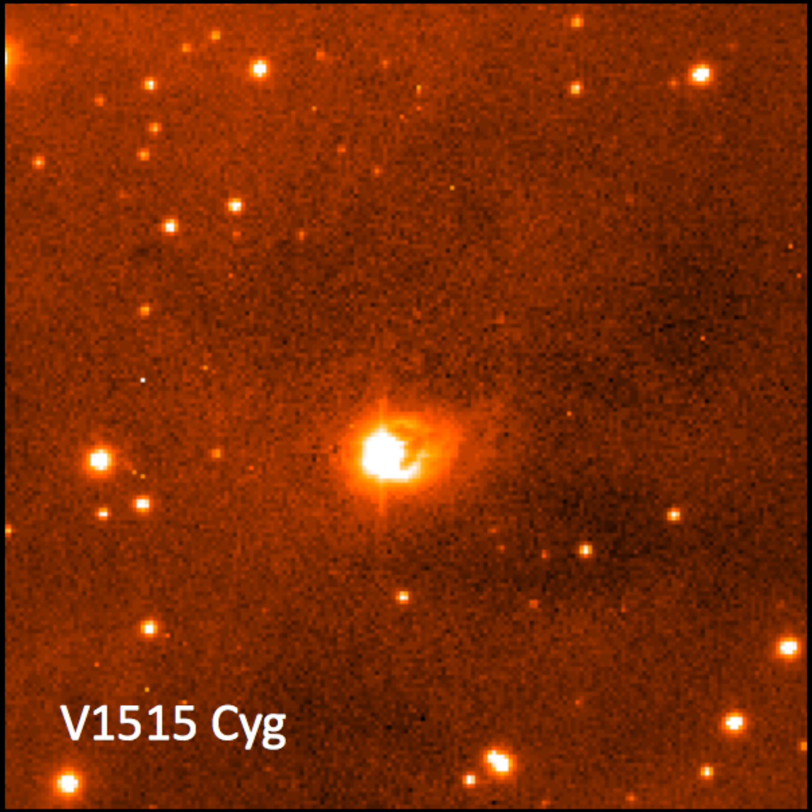
Much wider than blackbody

Zhu et al. 2008, ApJ 684, 1281

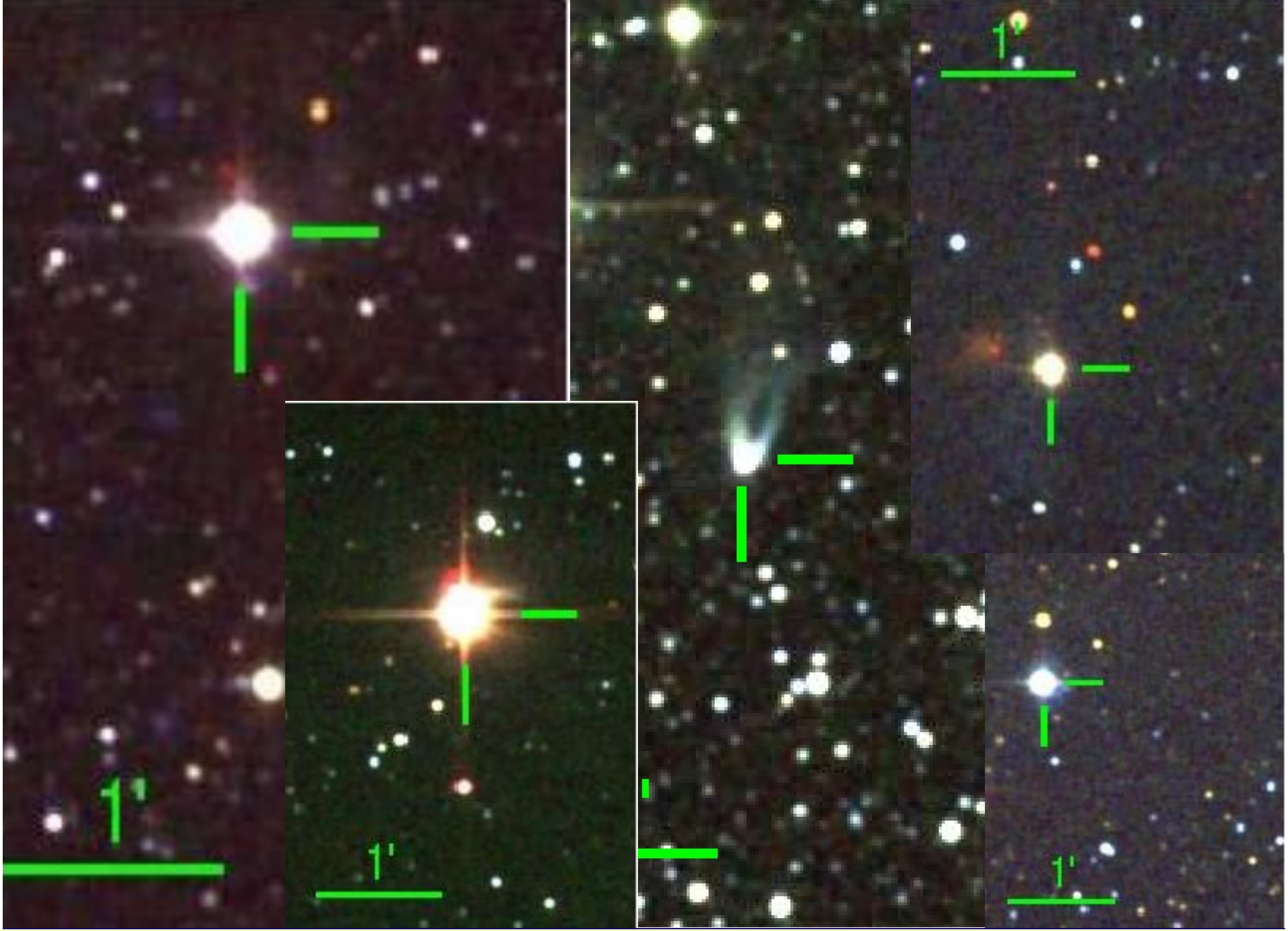
Additional FUors 1950-1978

Hartmann & Kenyon, 1996, ARAA, 34, 207





A few other stars with similar properties to FU Orionis were discovered, forming the “classical” FUor group (Herbig, 1977, ApJ, 217, 693; Elias, 1978, ApJ, 223, 859)


1'
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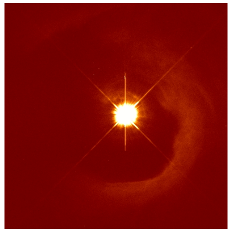
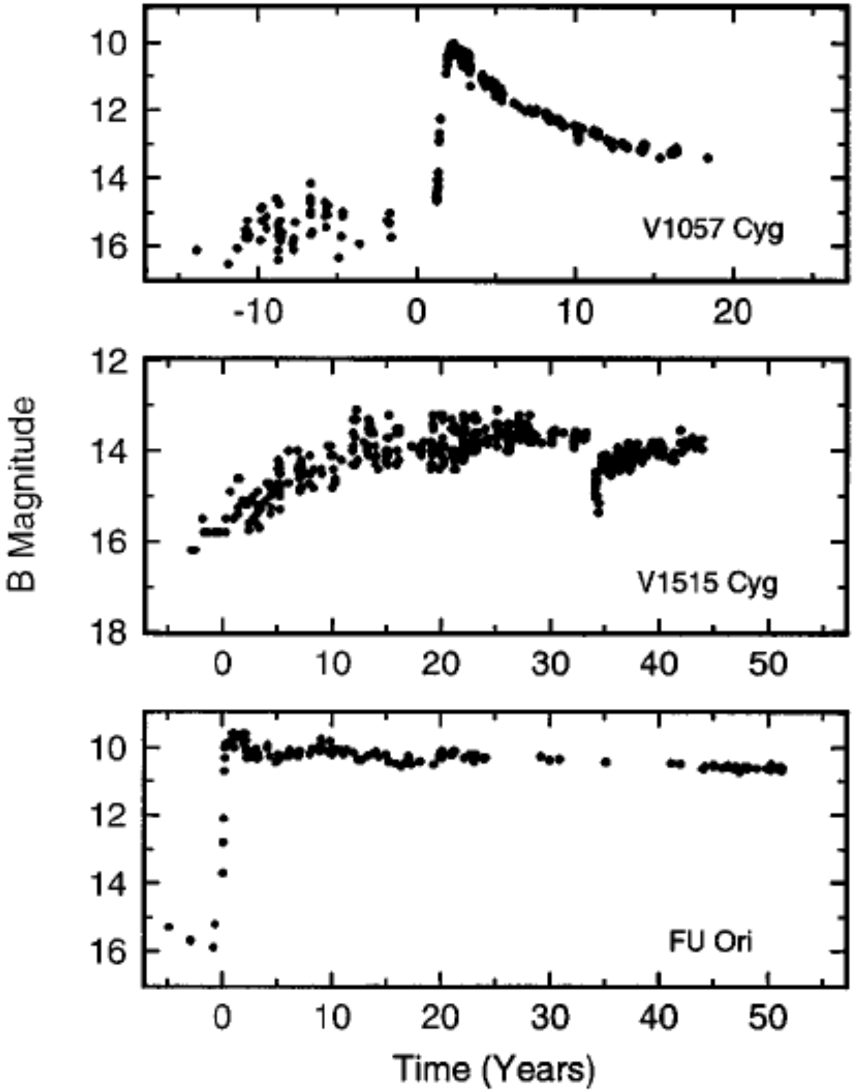
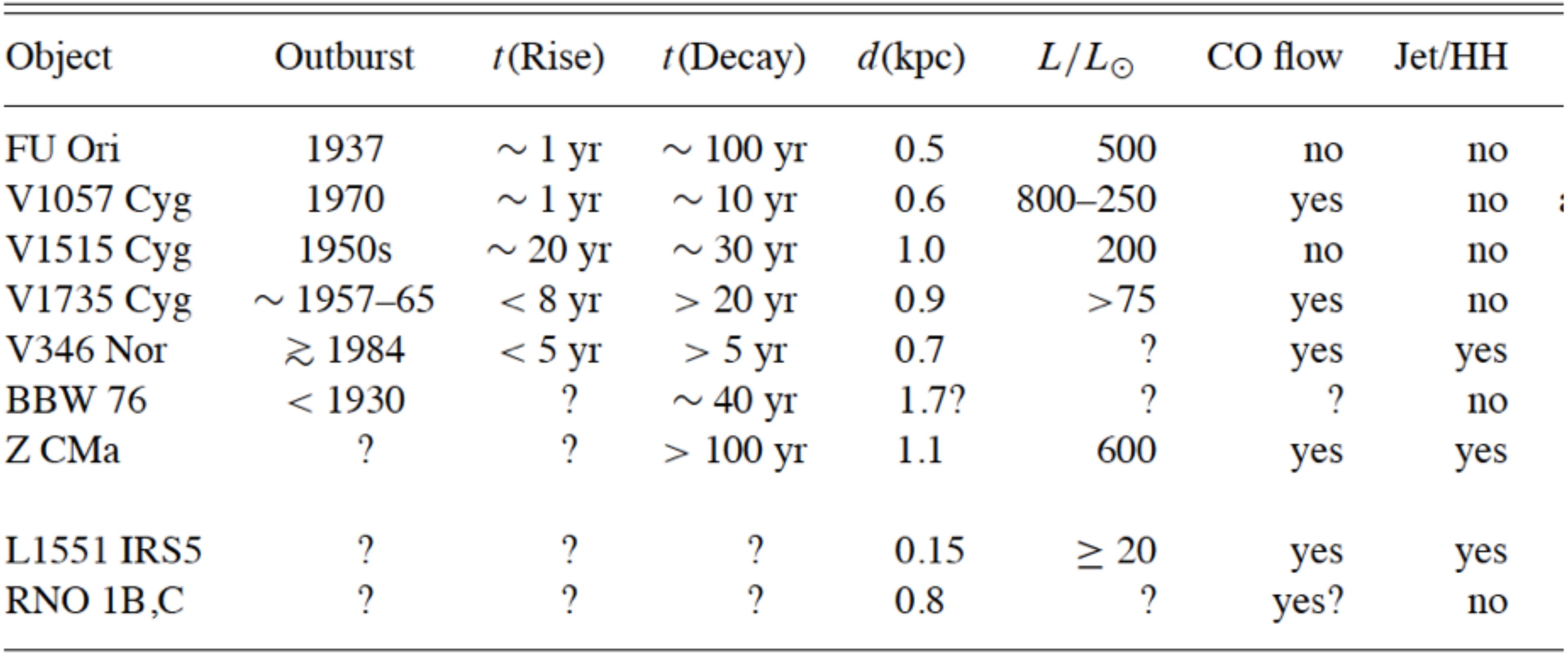
FU Orionis-type stars (FUors)



- Young stars with large outburst (4-5^m, 100x) in optical light (Herbig 1966, 1977)
- Outburst lightcurves are heterogeneous
- Reflection nebula, infrared excess
- Spectral type: F-G supergiant (optical) K-M giant or supergiant (near-infrared)
- Increased accretion up to 10^{-4} M_{sun}/yr (UV excess, hydrogen line intensity...)
- Special spectroscopic features: blueshifted absorption in Balmer lines, CO bandhead in absorption, double-peaked line profiles
- Temperature highest in the mid-plane



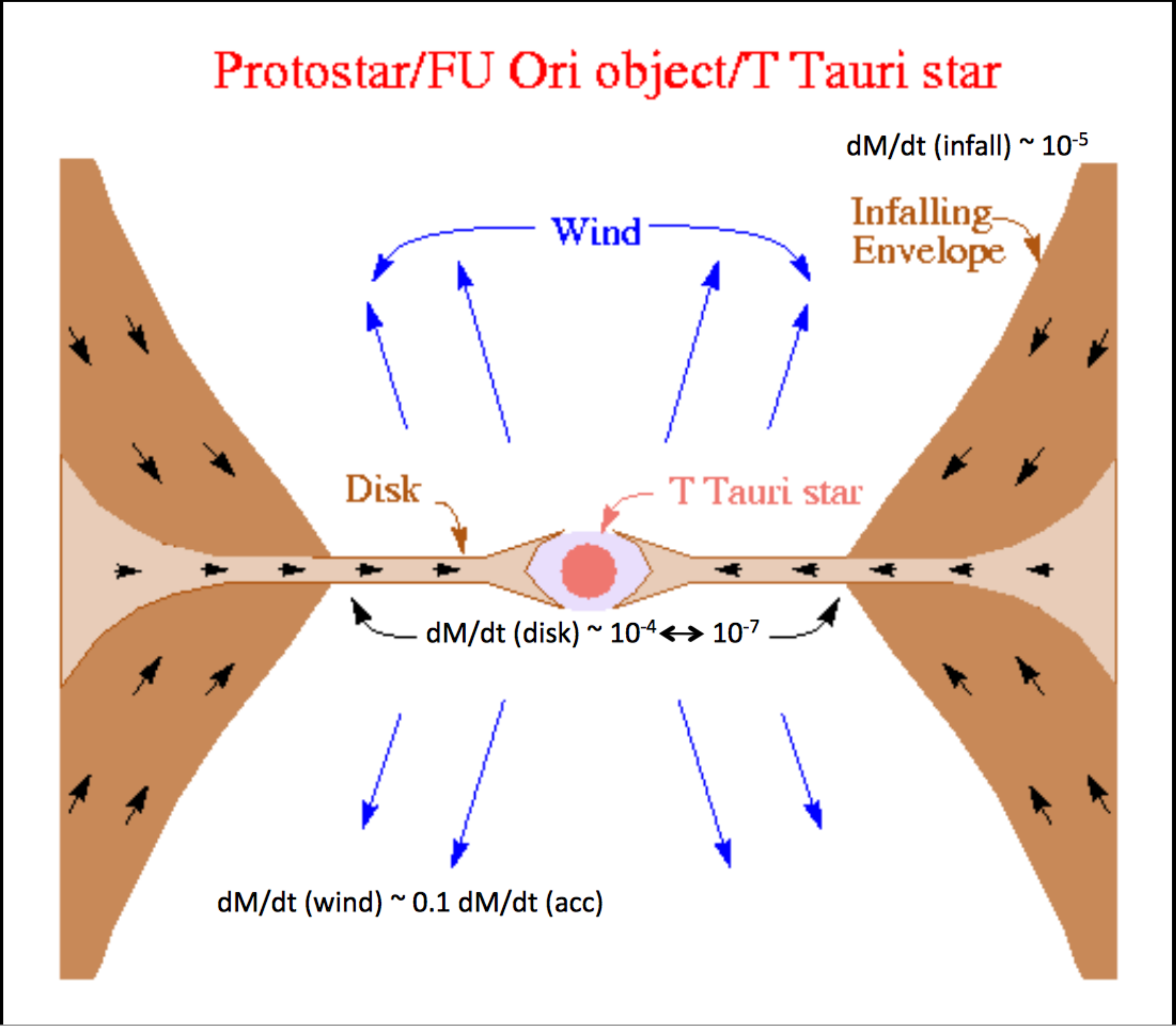
FU Orionis-type stars (FUors)



Object	Outburst	t(Rise)	t(Decay)	d(kpc)	$L/L_\odot$	CO flow	Jet/HH
FU Ori	1937	$\sim$ 1 yr	$\sim$ 100 yr	0.5	500	no	no
V1057 Cyg	1970	$\sim$ 1 yr	$\sim$ 10 yr	0.6	800–250	yes	no
V1515 Cyg	1950s	$\sim$ 20 yr	$\sim$ 30 yr	1.0	200	no	no
V1735 Cyg	$\sim$ 1957–65	$<$ 8 yr	$>$ 20 yr	0.9	$>$75	yes	no
V346 Nor	$\gtrsim$ 1984	$<$ 5 yr	$>$ 5 yr	0.7	?	yes	yes
BBW 76	$<$ 1930	?	$\sim$ 40 yr	1.7?	?	?	no
Z CMa	?	?	$>$ 100 yr	1.1	600	yes	yes
L1551 IRS5	?	?	?	0.15	$\geq$ 20	yes	yes
RNO 1B,C	?	?	?	0.8	?	yes?	no

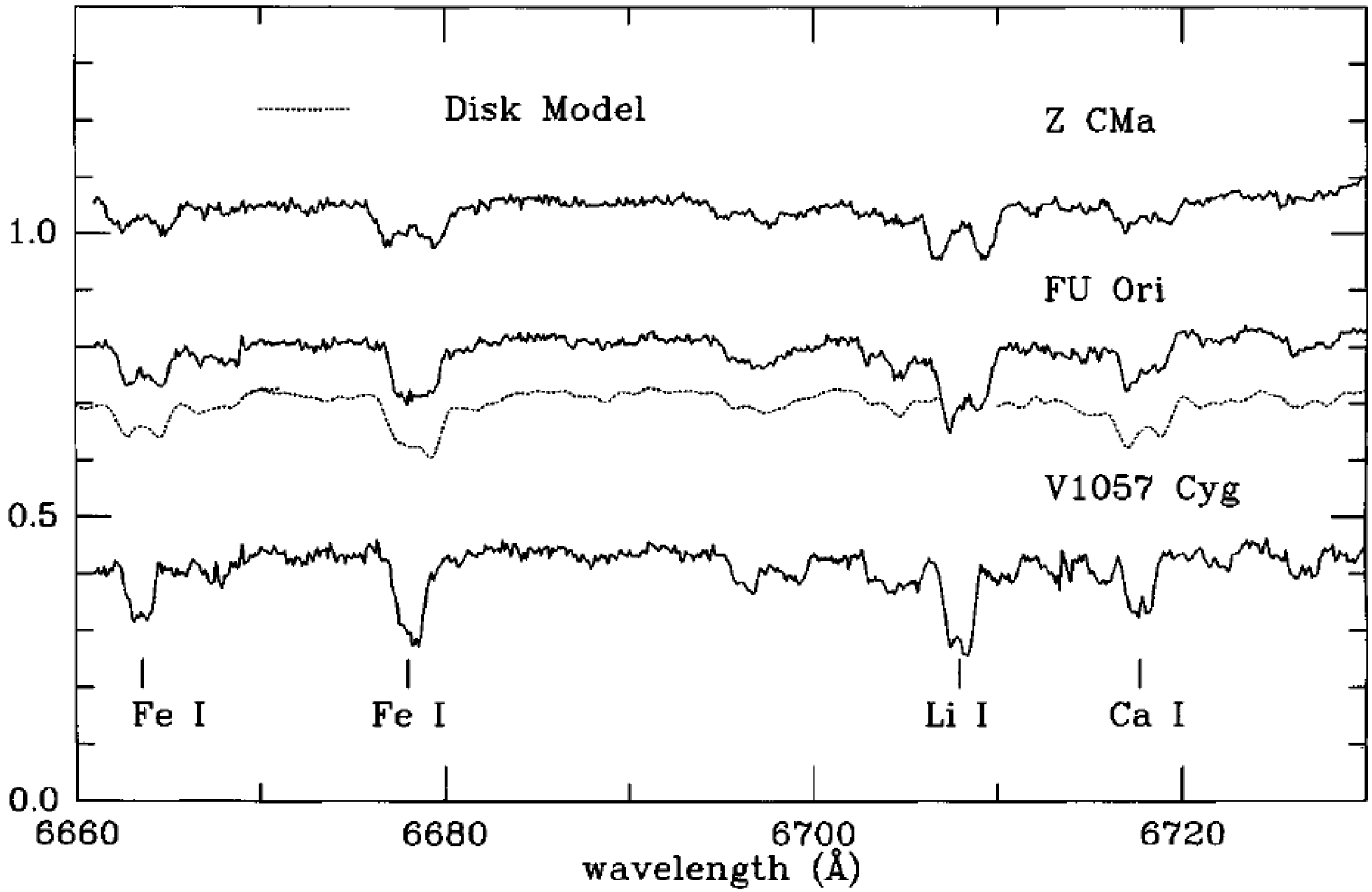
Hartmann & Kenyon (ARAA1996)

Protostar to Protoplanetary Disk: the Nature of Accretion



Modified from Hartmann & Kenyon, 1996, ARAA, 34, 207

Double-peaked line profiles

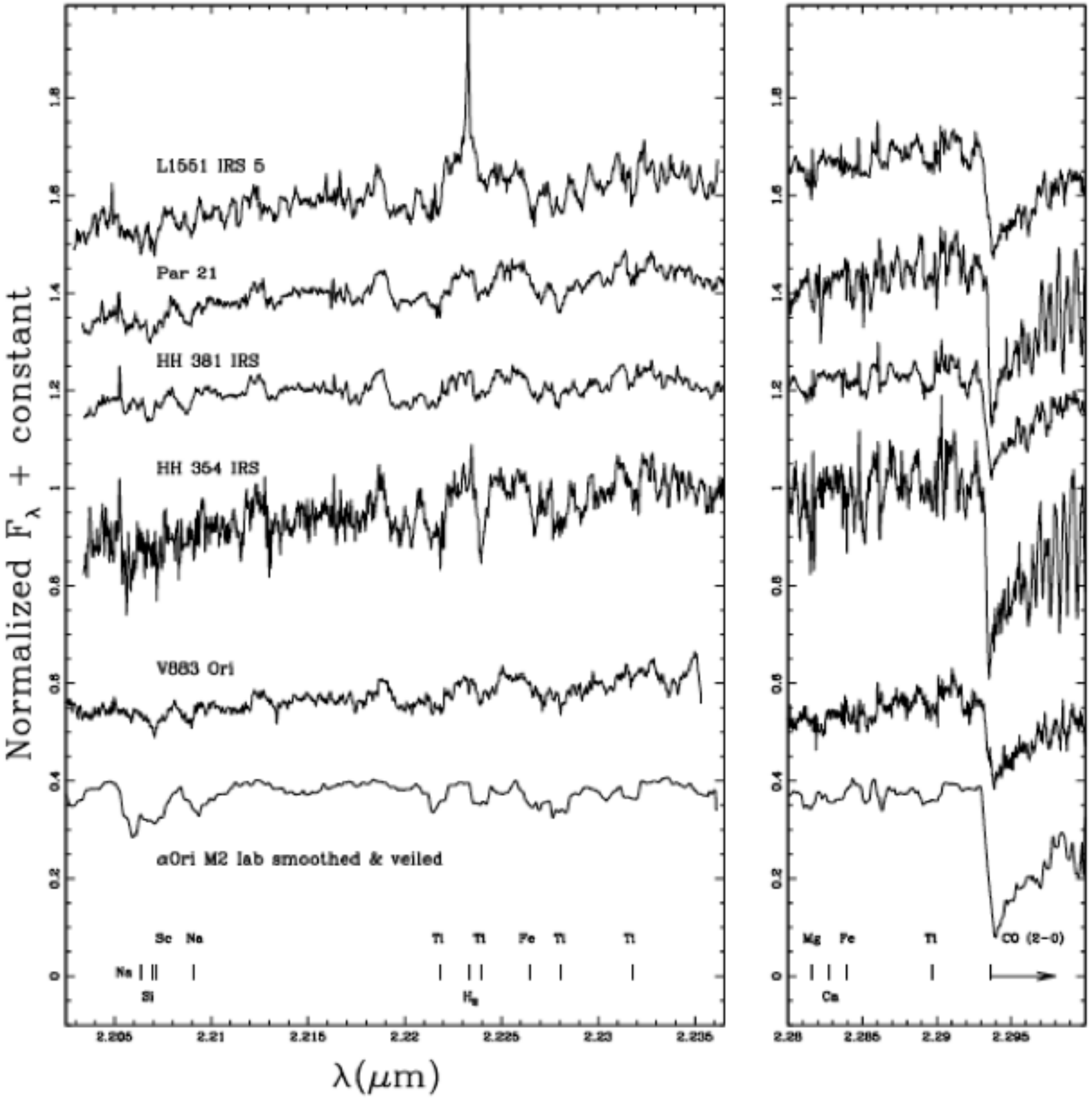


Hartmann & Kenyon (ARAA1996)

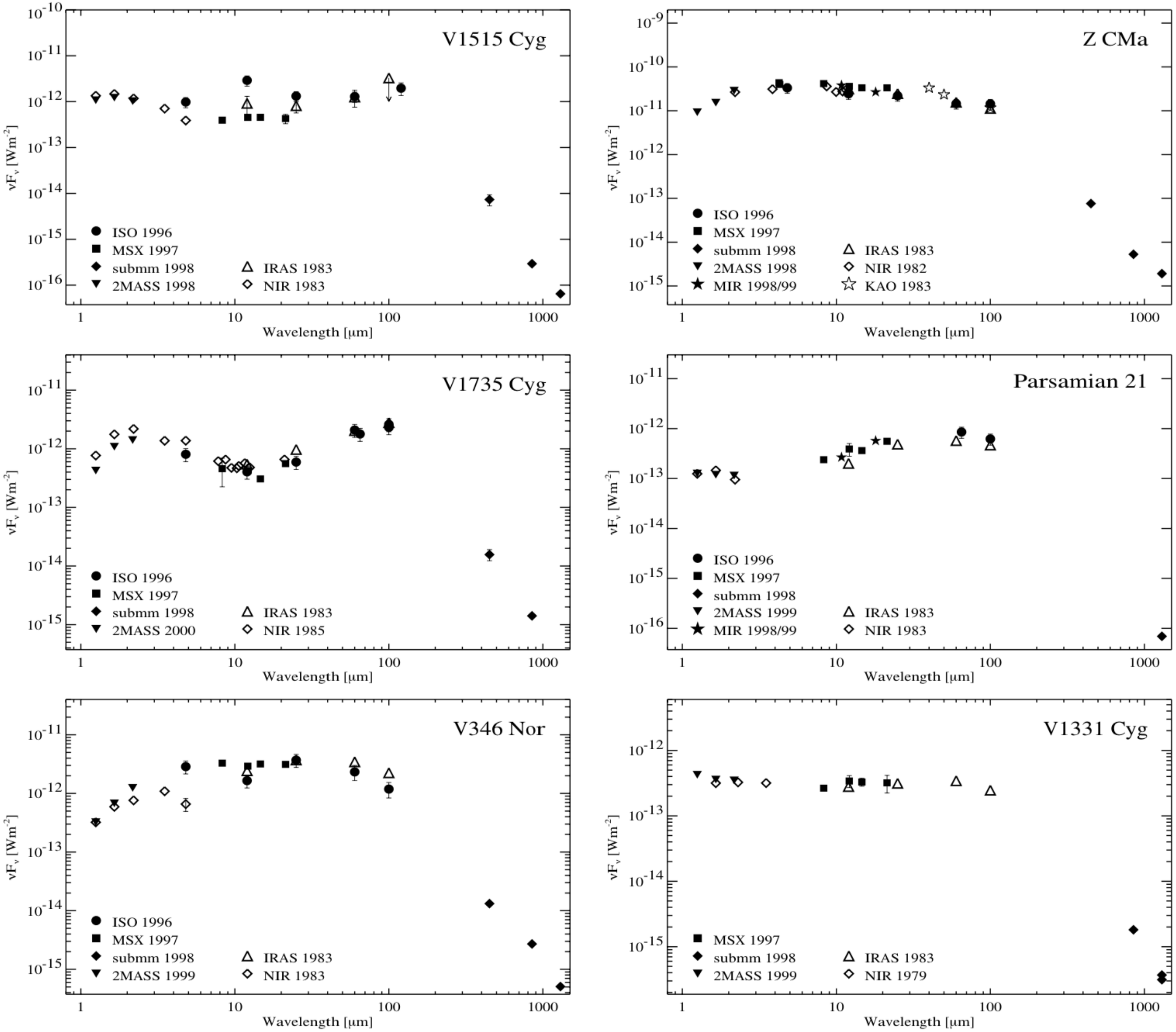
Expanding the FUor list

Since Herbig's original list, additional objects were proposed to joint the group:

- spectroscopic FUors
- Herbig-Haro sources as FUor candidates

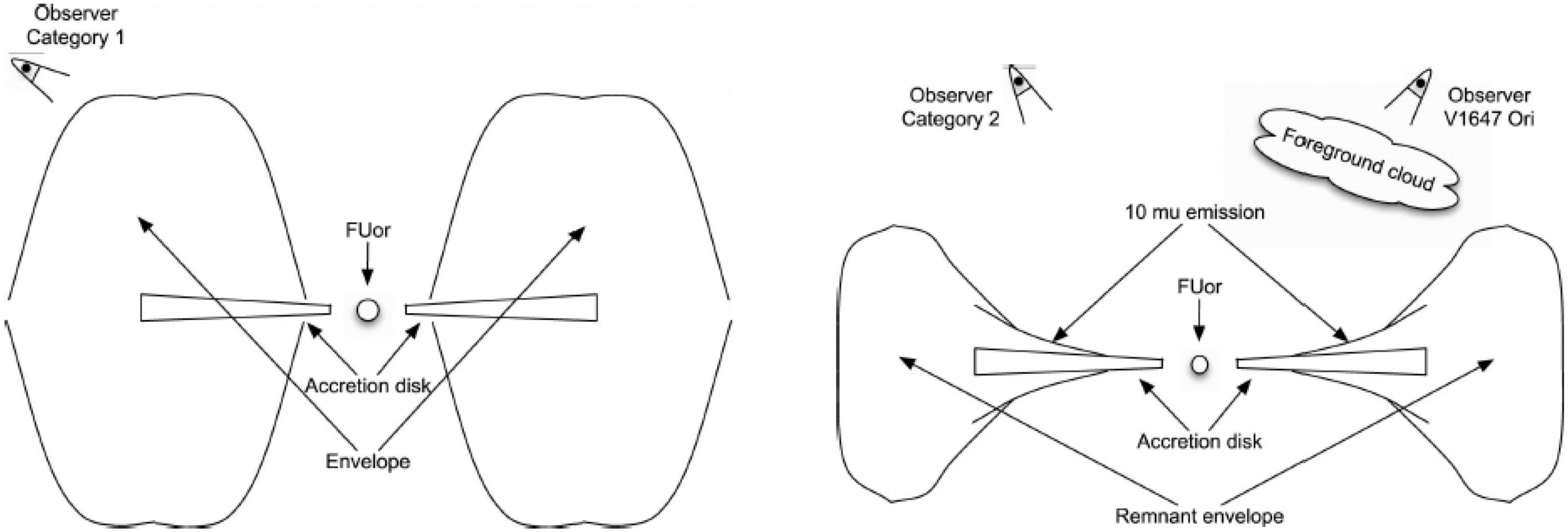


Greene et al. (2008)

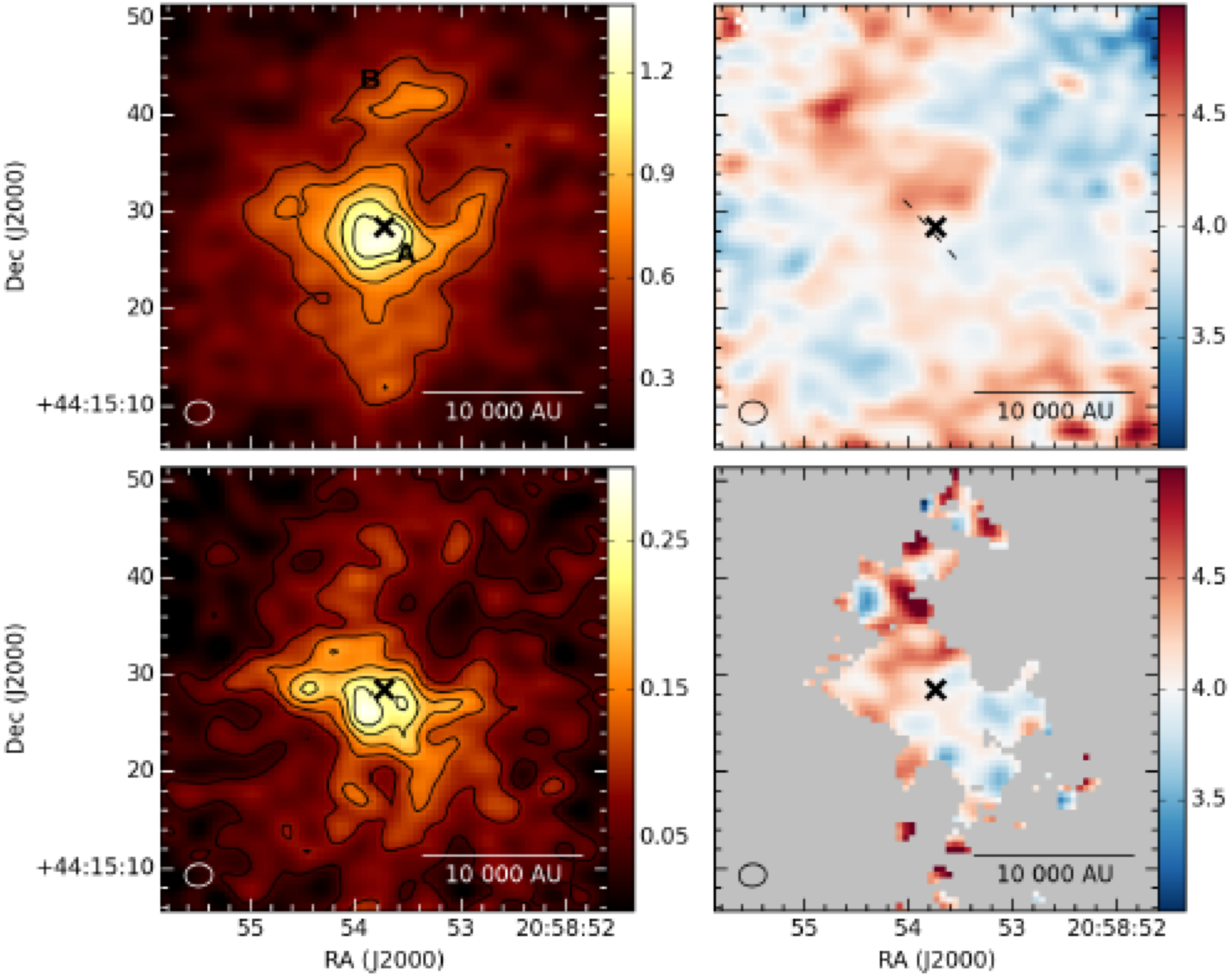


Ábrahám, Kóspál et al. (2004)

FU Orionis-type stars (FUors)

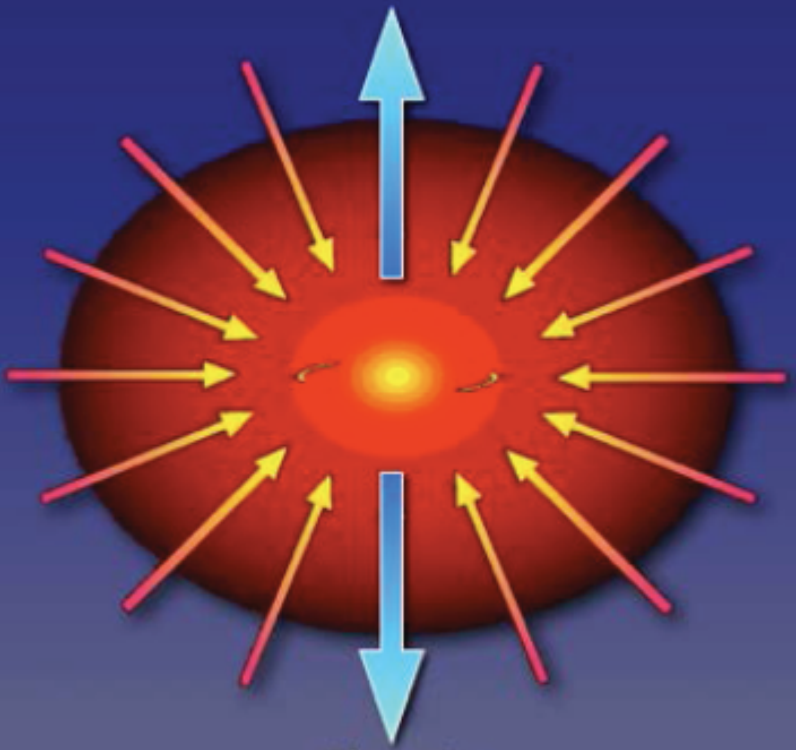


Sketch for the categories of FUors

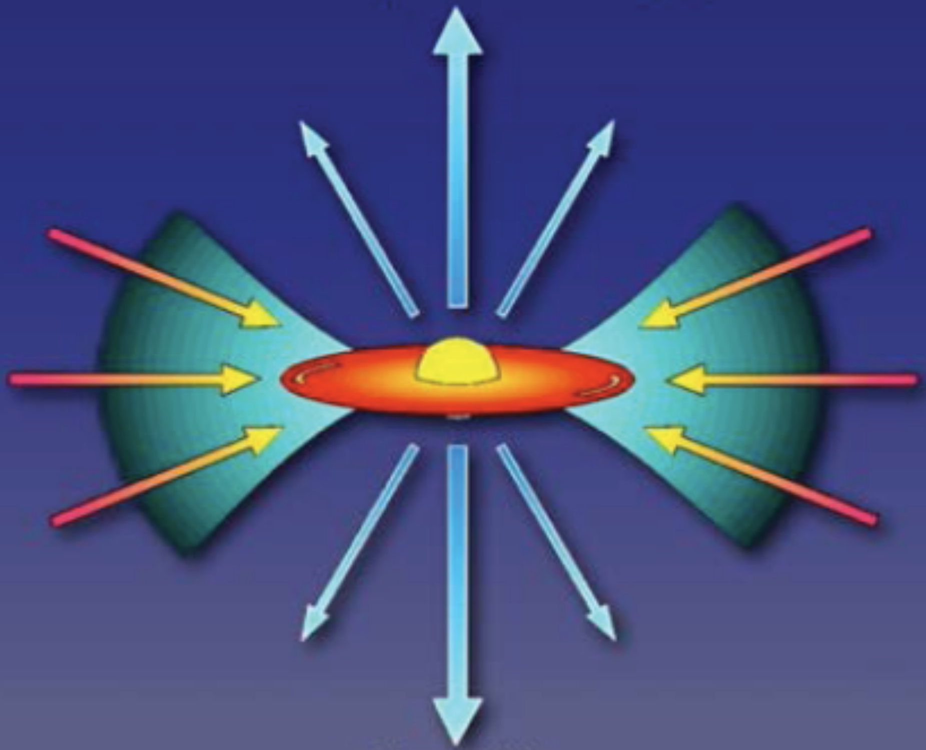


V1057 Cyg: J=1-0 transition of 13CO and C18CO
(left: intensity, right: velocity)
(Fehér et al. (in prep.)

The isolated star formation paradigm



Class 0:
10^4 yrs; 10-10^4 AU; 10-300 K



Class I-II:
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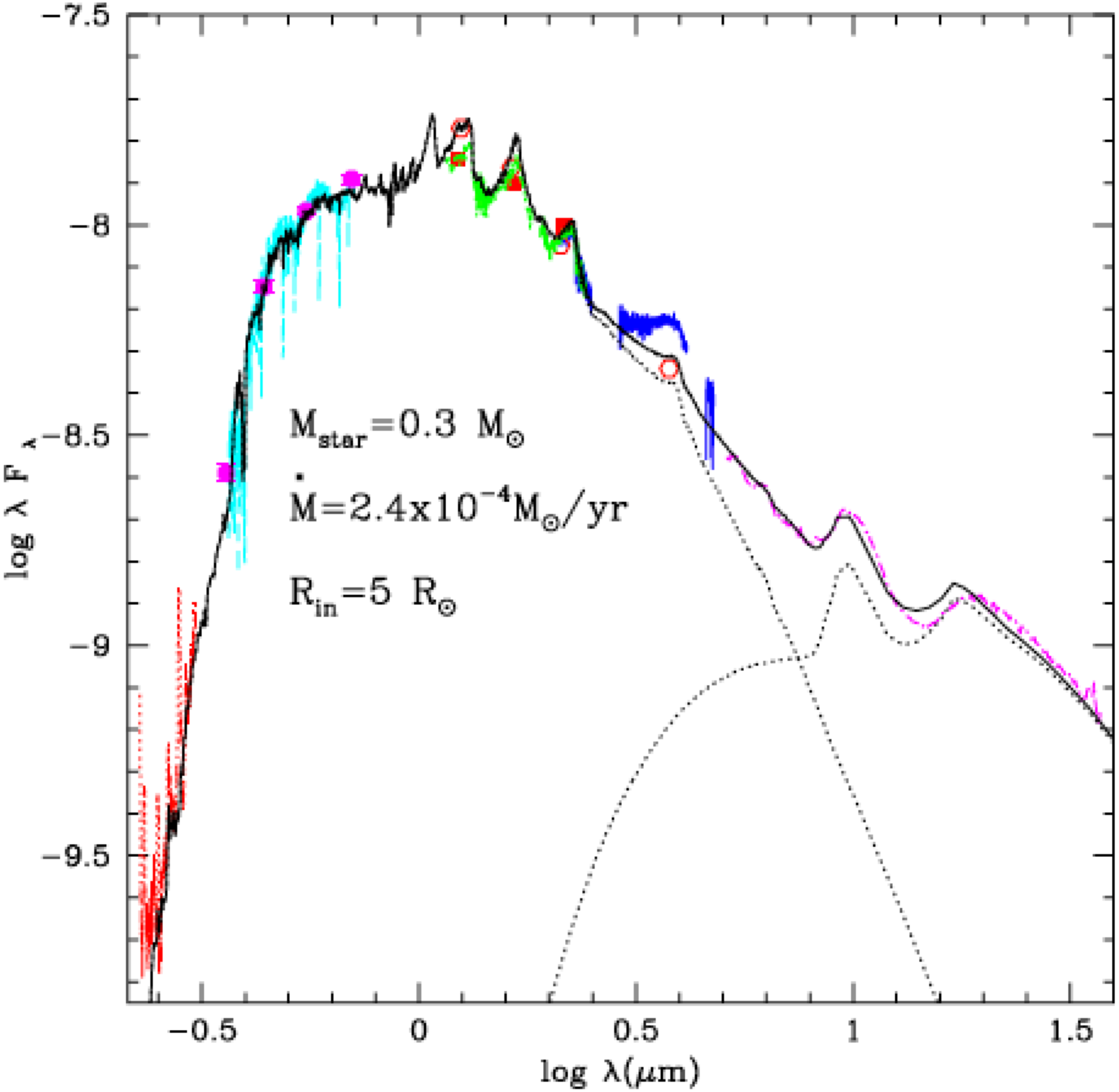
Class II-III:
$10^{6\text{-}7}$ yrs; 1-100 AU; 100-5000 K

Class IV:
$10^{7\text{-}9}$ yrs; 1-100 AU; 100-5000 K

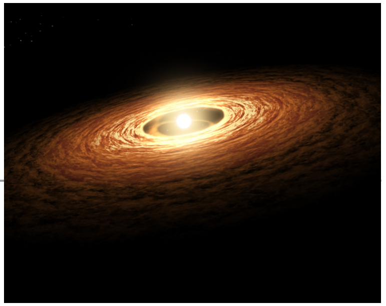
Courtesy of Mark McCaughrean

After Shu, Adams, & Lada

SED of FU Orionis

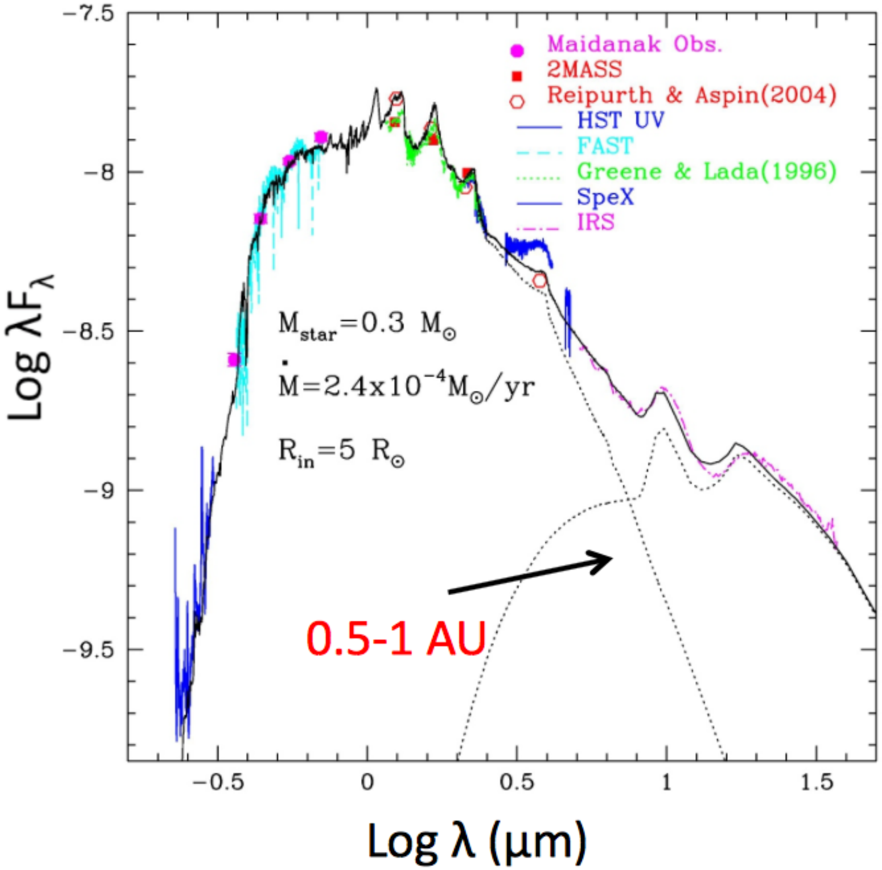


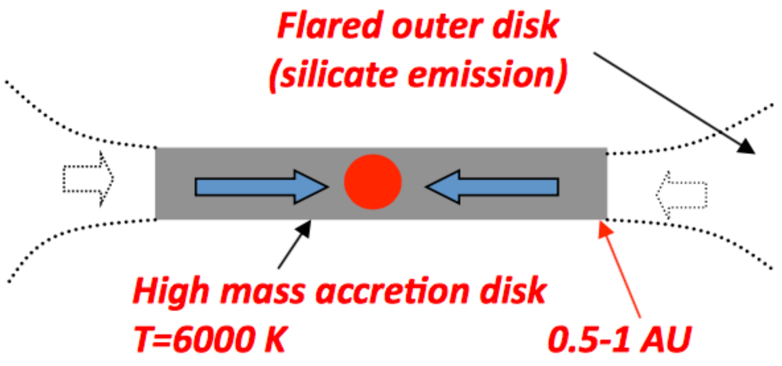
Outburst mechanisms



- **Matter is (1) accumulated then (2) falls onto the star**
- Interactions of binary or multiple systems where tidal forces disturb the circumstellar disk (Bonnell & Bastien 1992)
- Thermal instabilities in the disk alone (Bell et al. 1995)
- Planet-disk interactions, where thermal instabilities in the disk are caused by the presence of a massive planet (Lodato & Clarke 2004)
- Gravitational instabilities in the disk due to the mass infall from the rotating envelope onto the disk (Vorobyov & Basu 2006)
- Slow accumulation of matter due to gravitational instability, triggering the magnetorotational instability, which leads to rapid accretion. Thermal instability is triggered in the inner disk (Zhu et al. 2009)
- Matter piling up at the corotation radius (D’Angelo 2010)

SED of FU Orionis



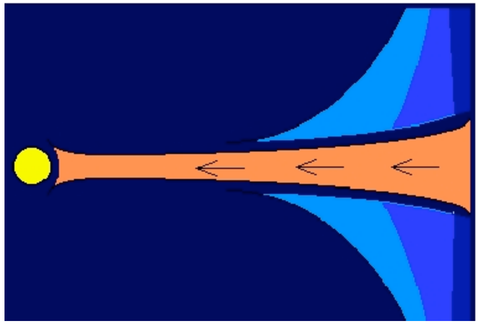


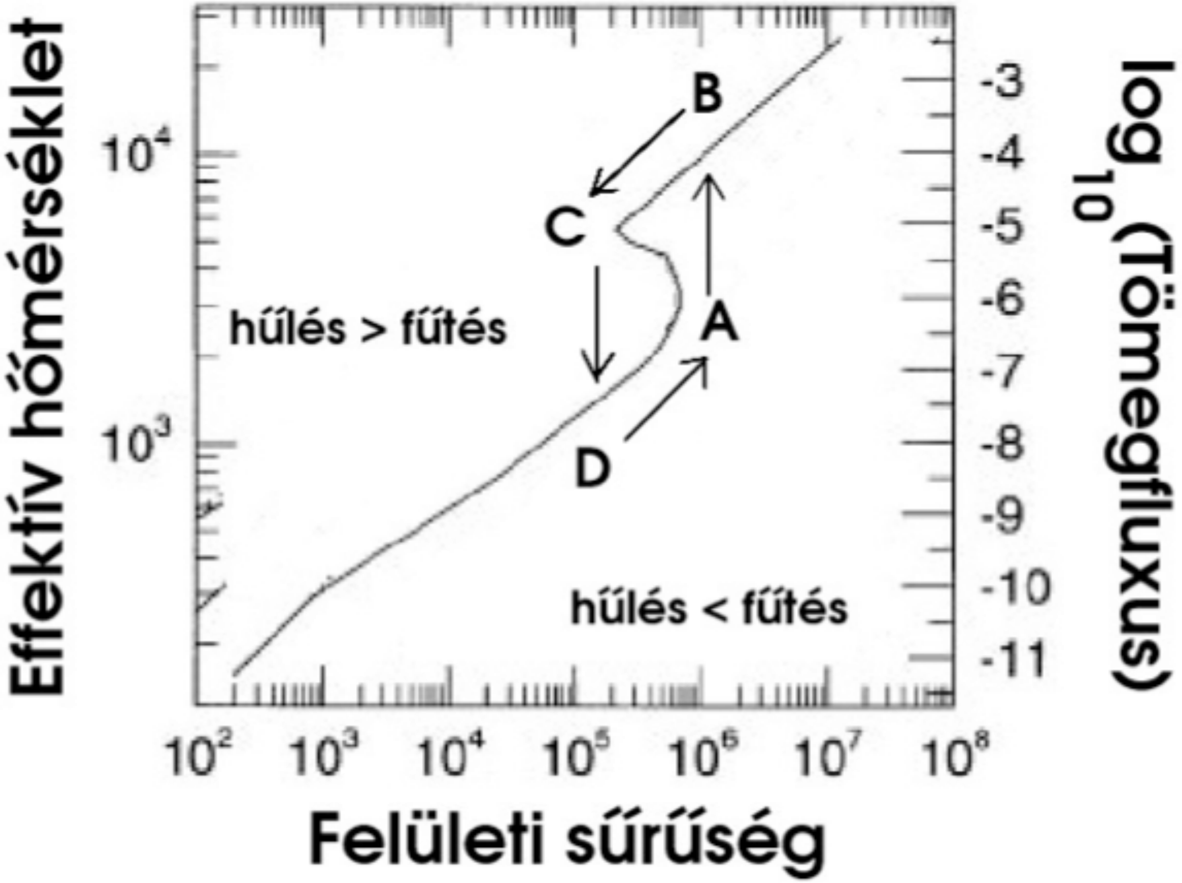
Zhu et al 2007, ApJ, 669, 483
Zhu et al. 2008, ApJ, 684, 1281

- Steady accretion model + hot inner disk extending from 5 $R_\odot$ to 0.5-1 AU
- Constrained by Keck (Eisner & Hillenbrand, 2011, ApJ, 738, 9) and MOST (Siwak et al. 2013, MNRAS, 432, 194)
- Decay timescale: $t_{visc} \sim R^2/\nu \Rightarrow \alpha \sim 0.01\text{-}0.1$

FU Orionis outbursts: physical reason?

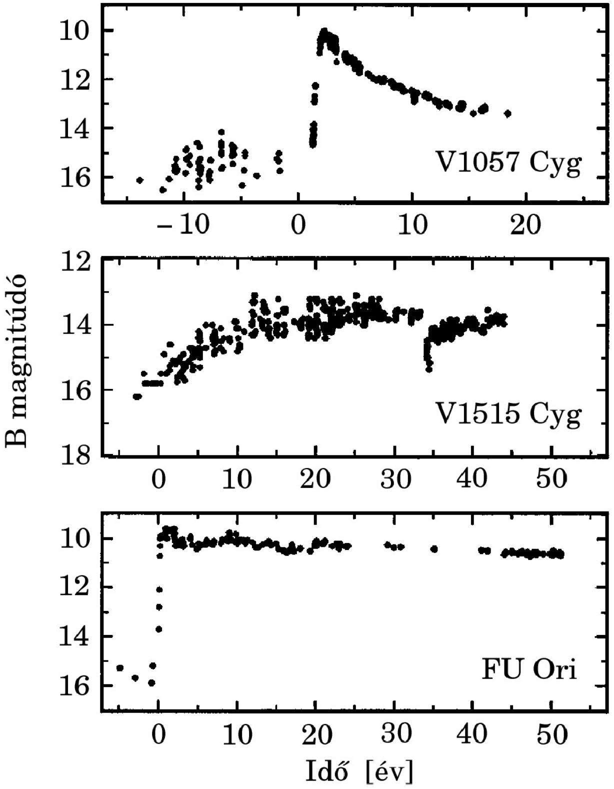
- Thermal instability





FU Orionis outbursts: physical reason?

- A korong először a belső peremén válik instabillá. Az ionizációs front belülről indul, és 10-20 évig halad kifelé egyre lassuló ütemben (V1515 Cyg esete).
- α=10^-3 kitörés közben
  α=10^-4 nyugalmi állapotban
- Akkréció a csillagra 10 ^-4 M_{nap} / év
- Egy kitörés mintegy 100 évig tart
- Gyors kitöréshez perturbáció kell, ekkor a front kívülről befelé gyorsulva halad
- Minden FU Ori csillag szoros kettős?



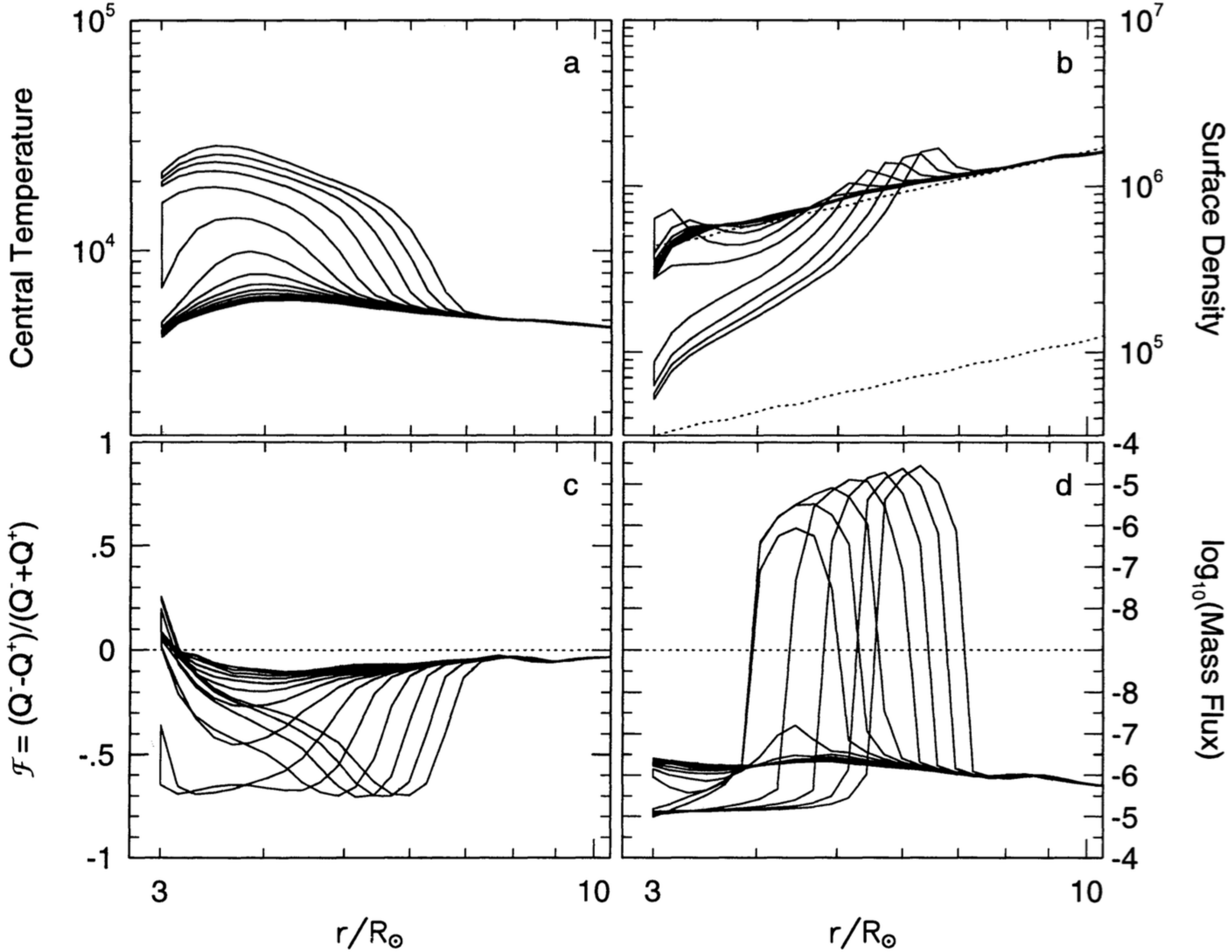


FIG. 4.—Onset of outburst: time evolution of radial distributions during time-dependent diffusion calculation of the "standard model" for which $\dot{M}_{\rm in} = 3 \times 10^{-6}\ M_\odot\ {\rm yr}^{-1}$, $\alpha_c = 10^{-4}$, and $\alpha_h = 10^{-3}$. Successive snapshots (14) are each separated by 1 yr for the inner disk region ($r = 3$–$10\ R_\odot$). (*a*) $T_c(r)$. Inner regions heat during outburst. (*b*) $\Sigma(r)$. Upper and lower dashed lines indicate $\Sigma_A(r)$ and $\Sigma_B(r)$, respectively. Outburst initiated at radius where $\Sigma > \Sigma_A$. (*c*) $\mathscr{F}(r)$. Fractionalized heat imbalance: $\mathscr{F} = (Q^- - Q^+)/(Q^- + Q^+)$. Dashed line indicates condition for vertical thermal balance: $Q^- = Q^+$. Negative values indicate local thermal heating, positive values indicate cooling. (*d*) $\dot{M}(r)$. Dashed line indicates zero mass flux; below dashed line indicates matter flowing inward, above indicates matter flowing outward.

Bell et al. (1994)

FU Orionis outbursts: physical reason?

- Gravitational instability

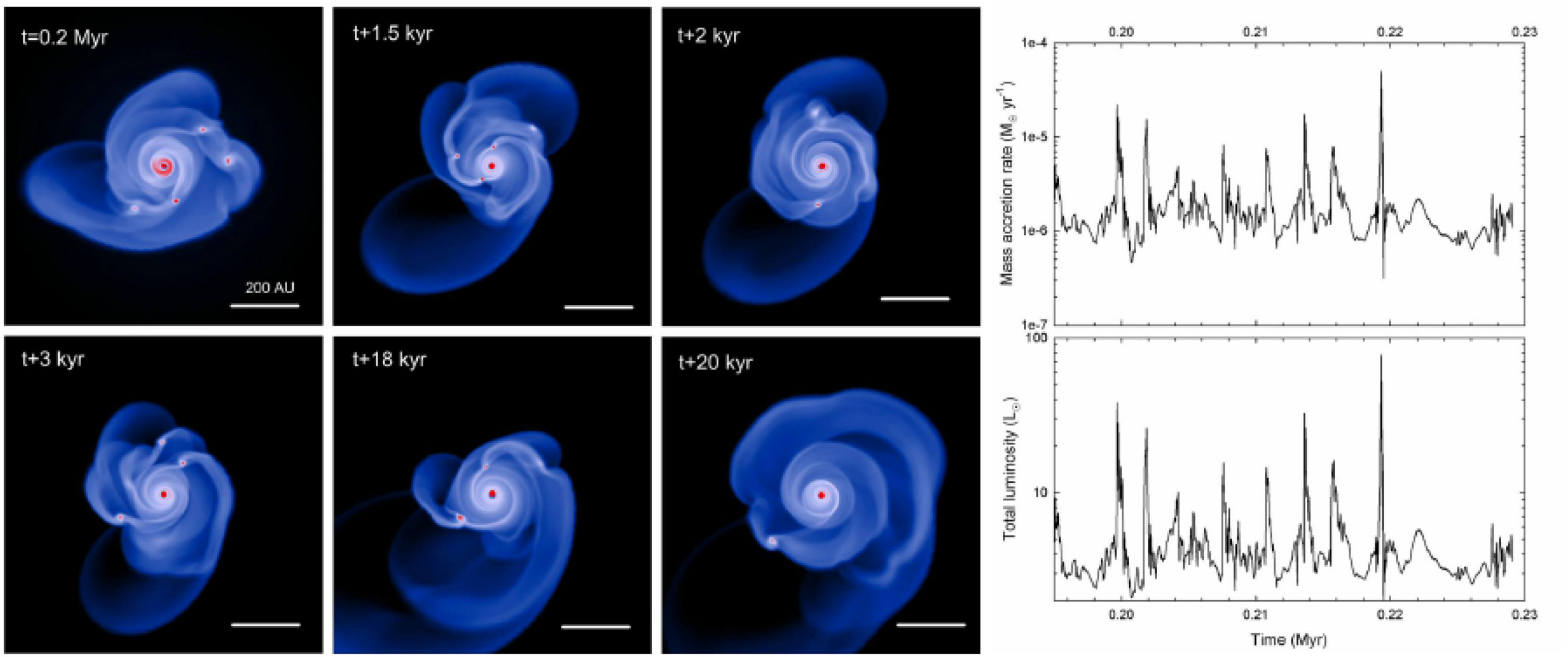
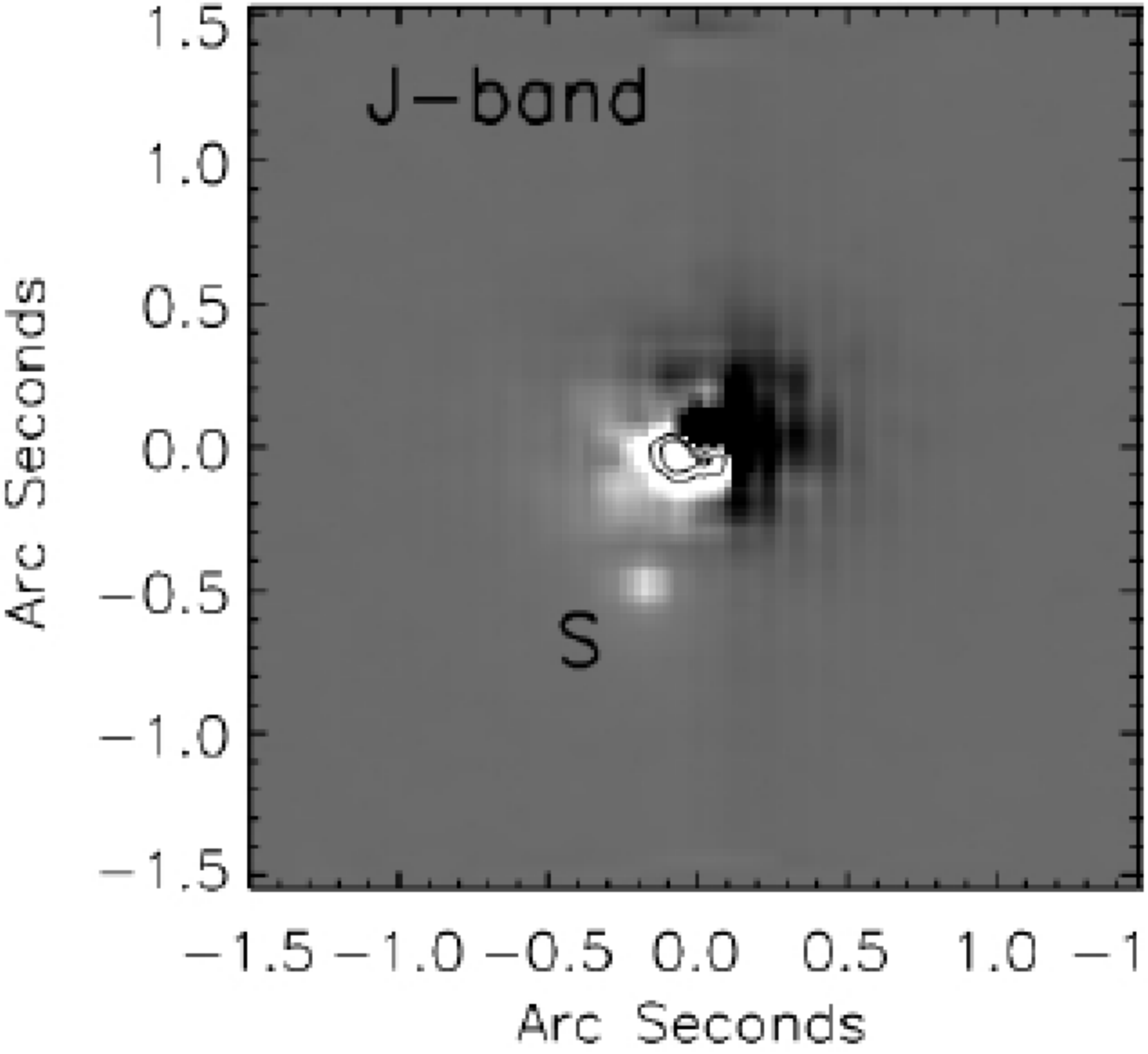


Fig. 1: Results of our hydrodynamical simulations that predict short-term variability and episodic bursts (based on Dunham & Vorobyov 2012), for a 0.4 $M_\odot$ central object (appropriate for FU Orionis). Left: model gas surface densities at several different time steps, showing vigorous gravitational instability and fragmentation. Right: time evolution of the mass accretion rate onto the star and the total luminosity of the system.

FU Orionis outbursts: physical reason?



FU Orionis

Wang et al. (2004)

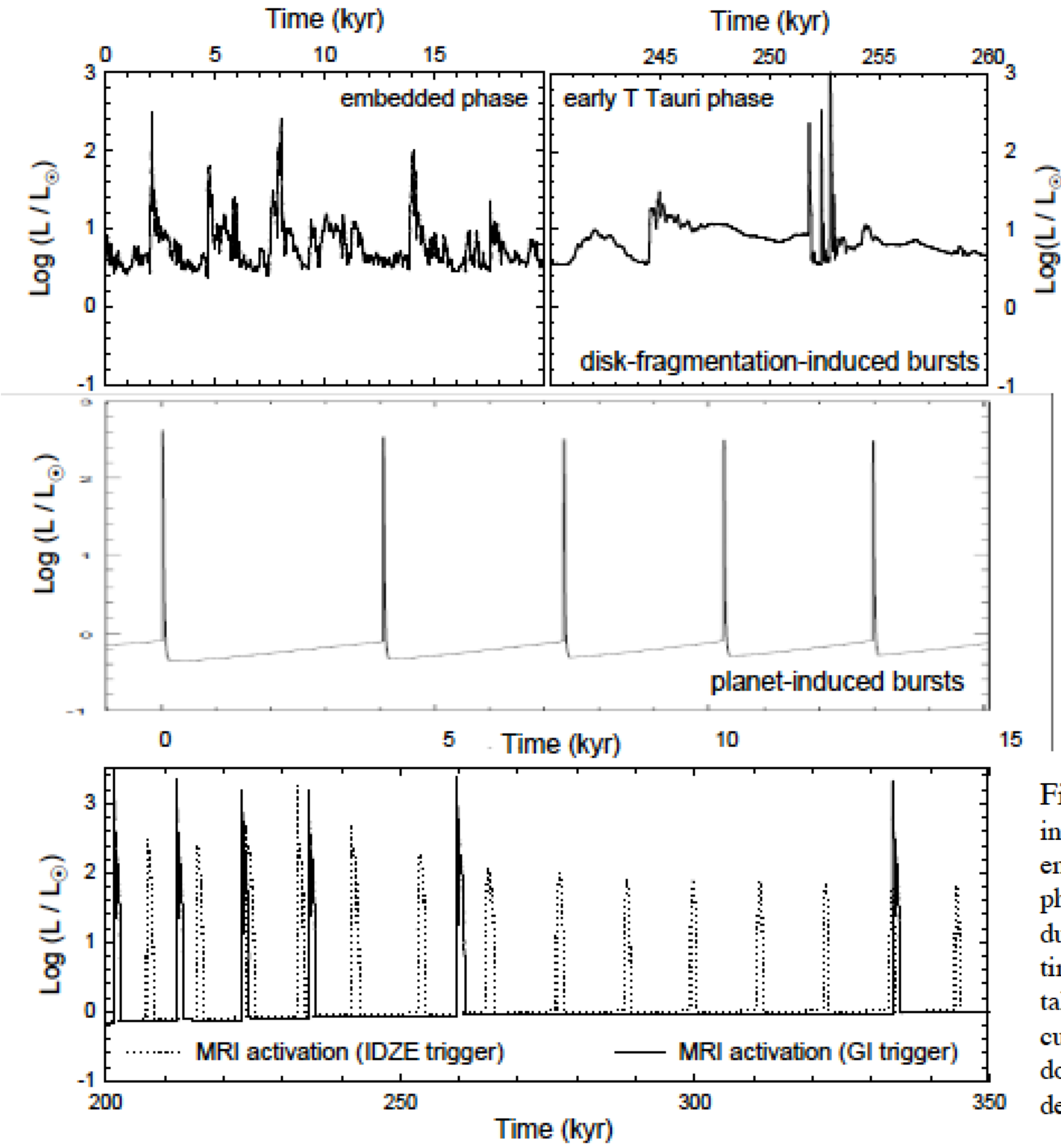


Fig. 6.— *Top:* Total (accretion plus photospheric) luminosity in the disk fragmentation model showing typical outbursts in the embedded phase of star formation (left) and in the early T Tauri phase (right). *Middle:* Bolometric lightcurves for the planet induced thermal instability model. Within this model the recurrence time between outbursts is reduced as time increases. *Bottom:* Total luminosity for the MRI thermally activation models. The solid curves are from models where MRI is triggered by GI, while the dotted curves are from models where MRI is activated at the inner dead zone edge (IDZE) due to a non-zero dead zone viscosity.

Audard et al. (2014)

Model outburst lightcurves

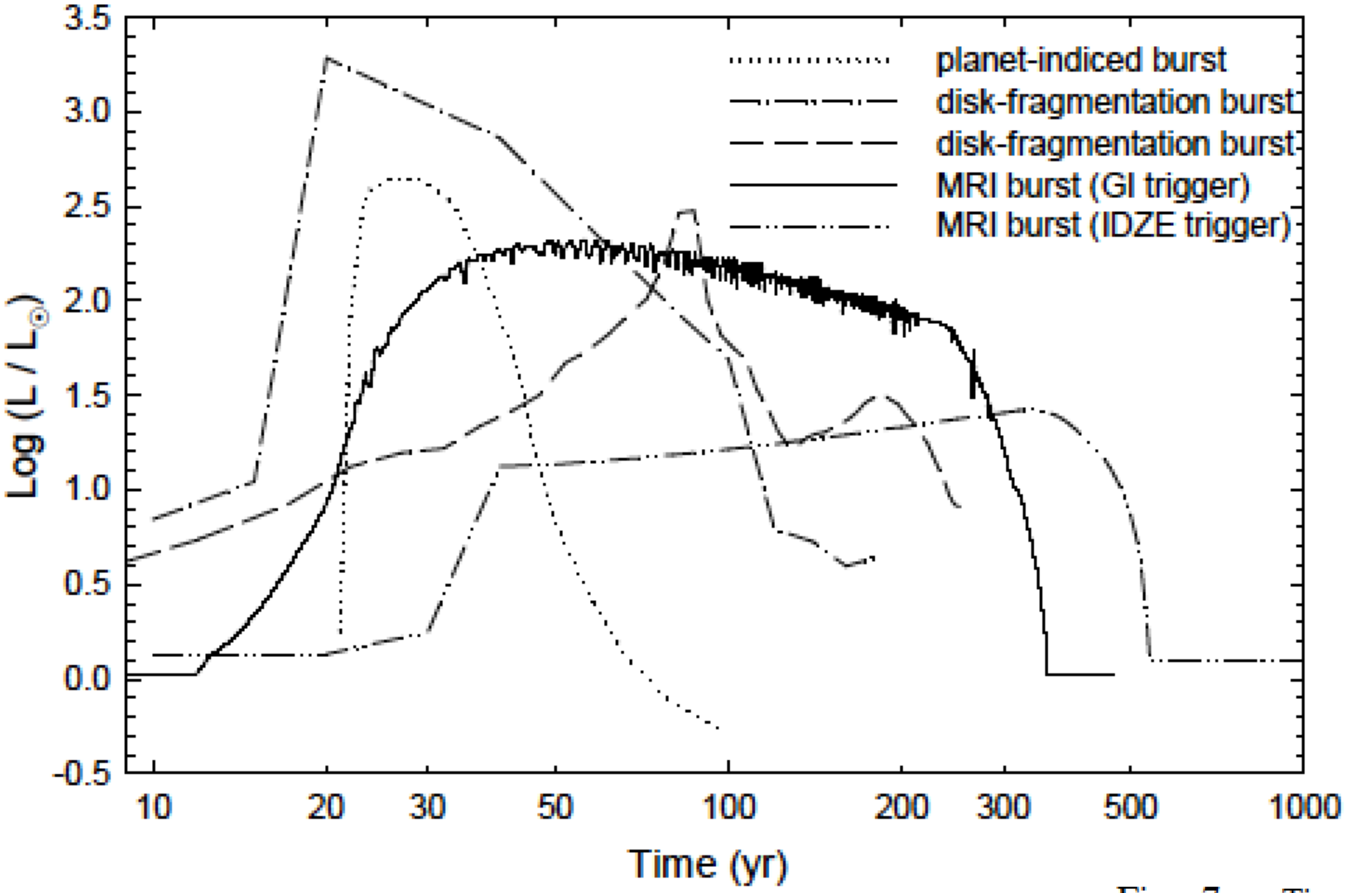


Fig. 7.— Time evolution of individual luminosity outbursts in different burst-triggering models. The zero-time is chosen arbitrarily to highlight distinct models. The two distinct outburst curves in the disk fragmentation model stem from the state of the fragment when accreted onto the star. Tidally smeared fragments give rise to a slowly rising curve (predominantly, in the embedded phase), while a sharply rising curve is produced by weakly perturbed fragments in the early T Tauri phase.

Audard et al. (2014)

How significant are the bursts?

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

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

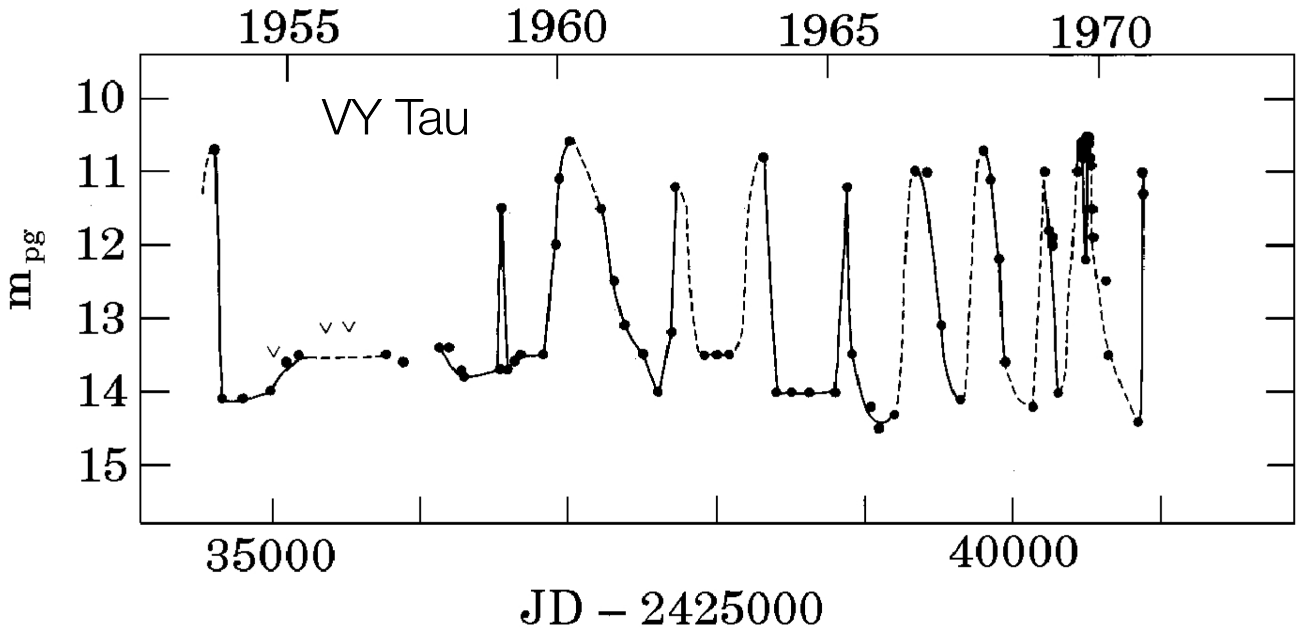
Within 1 kpc of the Sun:

$10^4 - 10^5$ T Tauri stars x avg. accretion rate $10^{-8}\ M_\odot\ yr^{-1} = 10^{-3}\ M_\odot\ yr^{-1}$
8 FUors, combined accretion rate ~ few x $10^{-4}\ M_\odot\ yr^{-1}$
-FUors are responsible for ~ 10% of the current nearby accretion

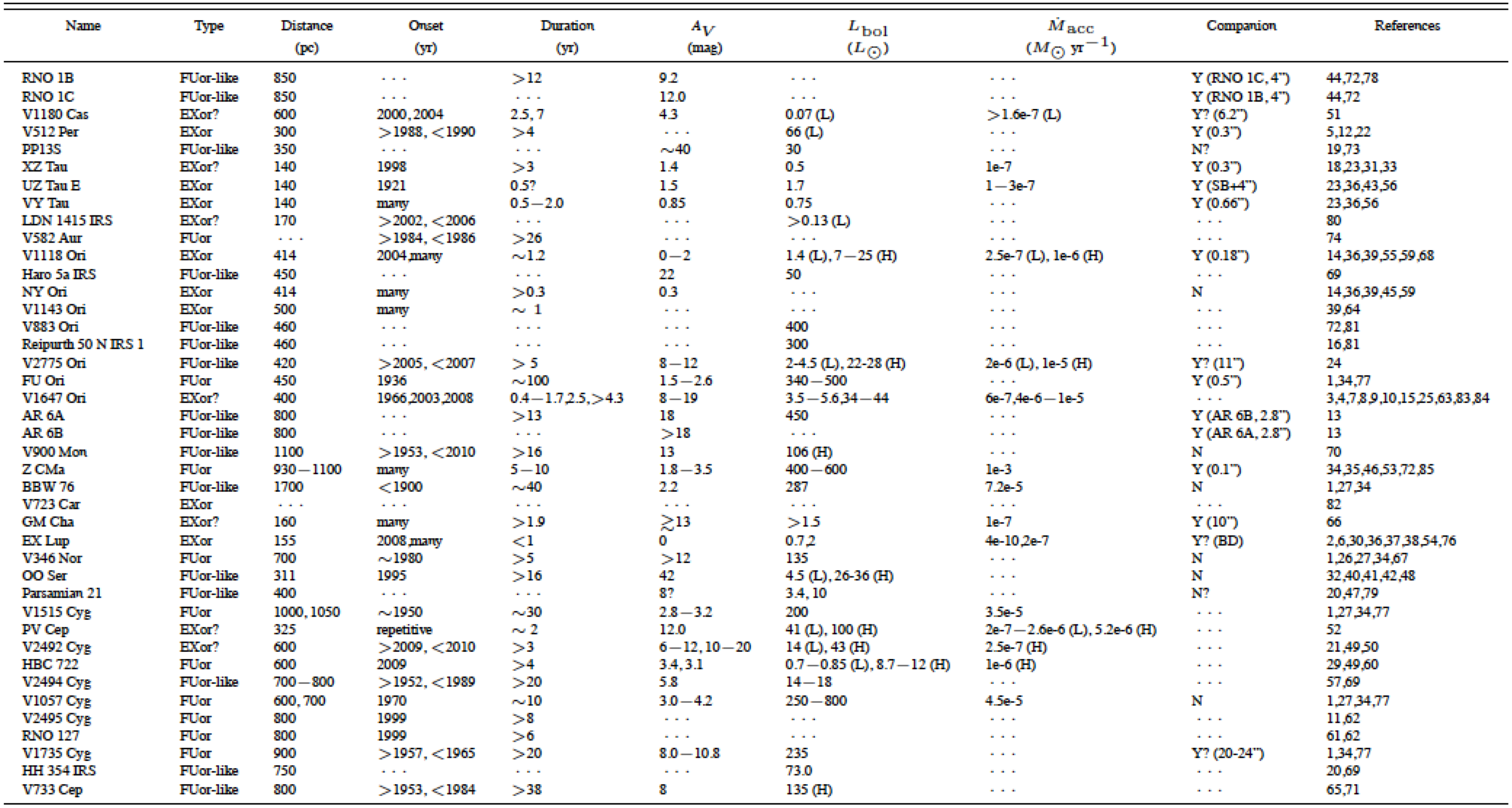
About 8 FUors since 1936; average star formation rate 1 / 50 yr
(FUor list updated from Reipurth & Aspin 2010, Evolution of Cosmic Objects through their Physical Activity, 19; star formation rate from Miller & Scalo 1979, ApJS, 41, 513; see also Offner & McKee 2011, ApJ, 736, 53)
-FUors occur at several times the rate of star formation; averaging multiple bursts per star

The little sisters: EX Lupi-type stars (EXors)

- Defined by Herbig (1977, 1989)
- Named after EX Lupi (and NOT after EX Orionis!)
- Episodic and repetitive eruptions, mass accretion rate: 10^{-6} - 10^{-7} M_{sun}/yr
- In quiescence spectra look like those of normal T Tauri stars
- In outburst: emission lines, accretion signatures, CO bandhead in emission



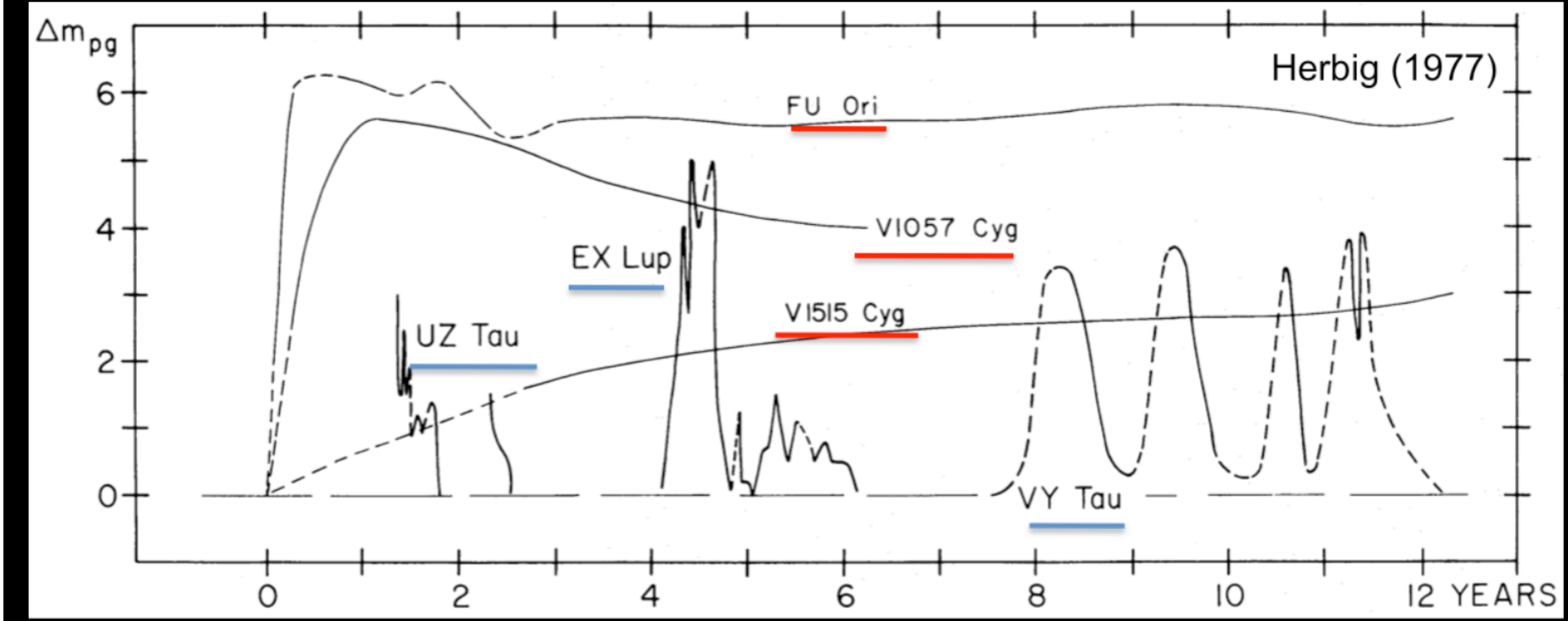
Recent inventory of eruptive stars (FUor + EXor)



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	References
RNO 1B	FUor-like	850	···	>12	9.2	···	···	Y (RNO 1C, 4")	44,72,78
RNO 1C	FUor-like	850	···	···	12.0	···	···	Y (RNO 1B, 4")	44,72
V1180 Cas	EXor?	600	2000, 2004	2.5, 7	4.3	0.07 (L)	>1.6e-7 (L)	Y? (6.2")	51
V512 Per	EXor	300	>1988, <1990	>4	···	66 (L)	···	Y (0.3")	5,12,22
PP13S	FUor-like	350	···	···	∼40	30	···	N?	19,73
XZ Tau	EXor?	140	1998	>3	1.4	0.5	1e-7	Y (0.3")	18,23,31,33
UZ Tau E	EXor	140	1921	0.5?	1.5	1.7	1—3e-7	Y (SB+4")	23,36,43,56
VY Tau	EXor	140	many	0.5—2.0	0.85	0.75	···	Y (0.66")	23,36,56
LDN 1415 IRS	EXor?	170	>2002, <2006	···	···	>0.13 (L)	···	···	80
V582 Aur	FUor	···	>1984, <1986	>26	···	···	···	···	74
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")	14,36,39,55,59,68
Haro 5a IRS	FUor-like	450	···	···	22	50	···	···	69
NY Ori	EXor	414	many	>0.3	0.3	···	···	N	14,36,39,45,59
V1143 Ori	EXor	500	many	∼ 1	···	···	···	···	39,64
V883 Ori	FUor-like	460	···	···	···	400	···	···	72,81
Reipurth 50 N IRS 1	FUor-like	460	···	···	···	300	···	···	16,81
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")	24
FU Ori	FUor	450	1936	∼100	1.5—2.6	340—500	···	Y (0.5")	1,34,77
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	···	3,4,7,8,9,10,15,25,63,83,84
AR 6A	FUor-like	800	···	>13	18	450	···	Y (AR 6B, 2.8")	13
AR 6B	FUor-like	800	···	···	>18	···	···	Y (AR 6A, 2.8")	13
V900 Mon	FUor-like	1100	>1953, <2010	>16	13	106 (H)	···	N	70
Z CMa	FUor	930—1100	many	5—10	1.8—3.5	400—600	1e-3	Y (0.1")	34,35,46,53,72,85
BBW 76	FUor-like	1700	<1900	∼40	2.2	287	7.2e-5	N	1,27,34
V723 Car	EXor	···	···	···	···	···	···	···	82
GM Cha	EXor?	160	many	>1.9	≳13	>1.5	1e-7	Y (10")	66
EX Lup	EXor	155	2008,many	<1	0	0.7,2	4e-10,2e-7	Y? (BD)	2,6,30,36,37,38,54,76
V346 Nor	FUor	700	∼1980	>5	>12	135	···	N	1,26,27,34,67
OO Ser	FUor-like	311	1995	>16	42	4.5 (L), 26-36 (H)	···	N	32,40,41,42,48
Parsamian 21	FUor-like	400	···	···	8?	3.4, 10	···	N?	20,47,79
V1515 Cyg	FUor	1000, 1050	∼1950	∼30	2.8—3.2	200	3.5e-5	···	1,27,34,77
PV Cep	EXor?	325	repetitive	∼ 2	12.0	41 (L), 100 (H)	2e-7—2.6e-6 (L), 5.2e-6 (H)	···	52
V2492 Cyg	EXor?	600	>2009, <2010	>3	6—12, 10—20	14 (L), 43 (H)	2.5e-7 (H)	···	21,49,50
HBC 722	FUor	600	2009	>4	3.4, 3.1	0.7—0.85 (L), 8.7—12 (H)	1e-6 (H)	···	29,49,60
V2494 Cyg	FUor-like	700—800	>1952, <1989	>20	5.8	14—18	···	···	57,69
V1057 Cyg	FUor	600, 700	1970	∼10	3.0—4.2	250—800	4.5e-5	N	1,27,34,77
V2495 Cyg	FUor	800	1999	>8	···	···	···	···	11,62
RNO 127	FUor	800	1999	>6	···	···	···	···	61,62
V1735 Cyg	FUor	900	>1957, <1965	>20	8.0—10.8	235	···	Y? (20-24")	1,34,77
HH 354 IRS	FUor-like	750	···	···	···	73.0	···	···	20,69
V733 Cep	FUor-like	800	>1953, <1984	>38	8	135 (H)	···	···	65,71

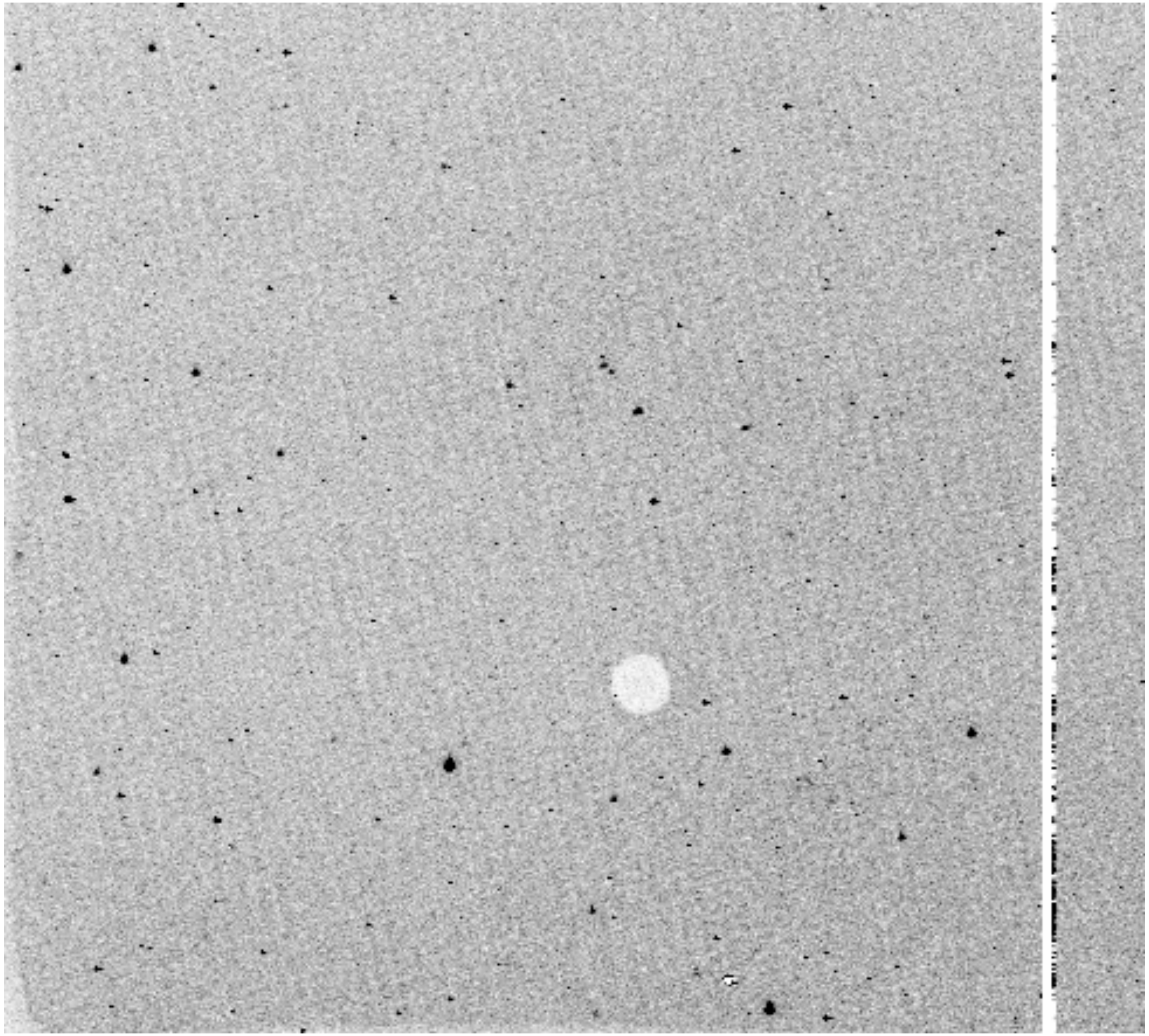
Audard et al. (PPVI 2014)

EXor Timescales Allow Characterization of the Complete Burst

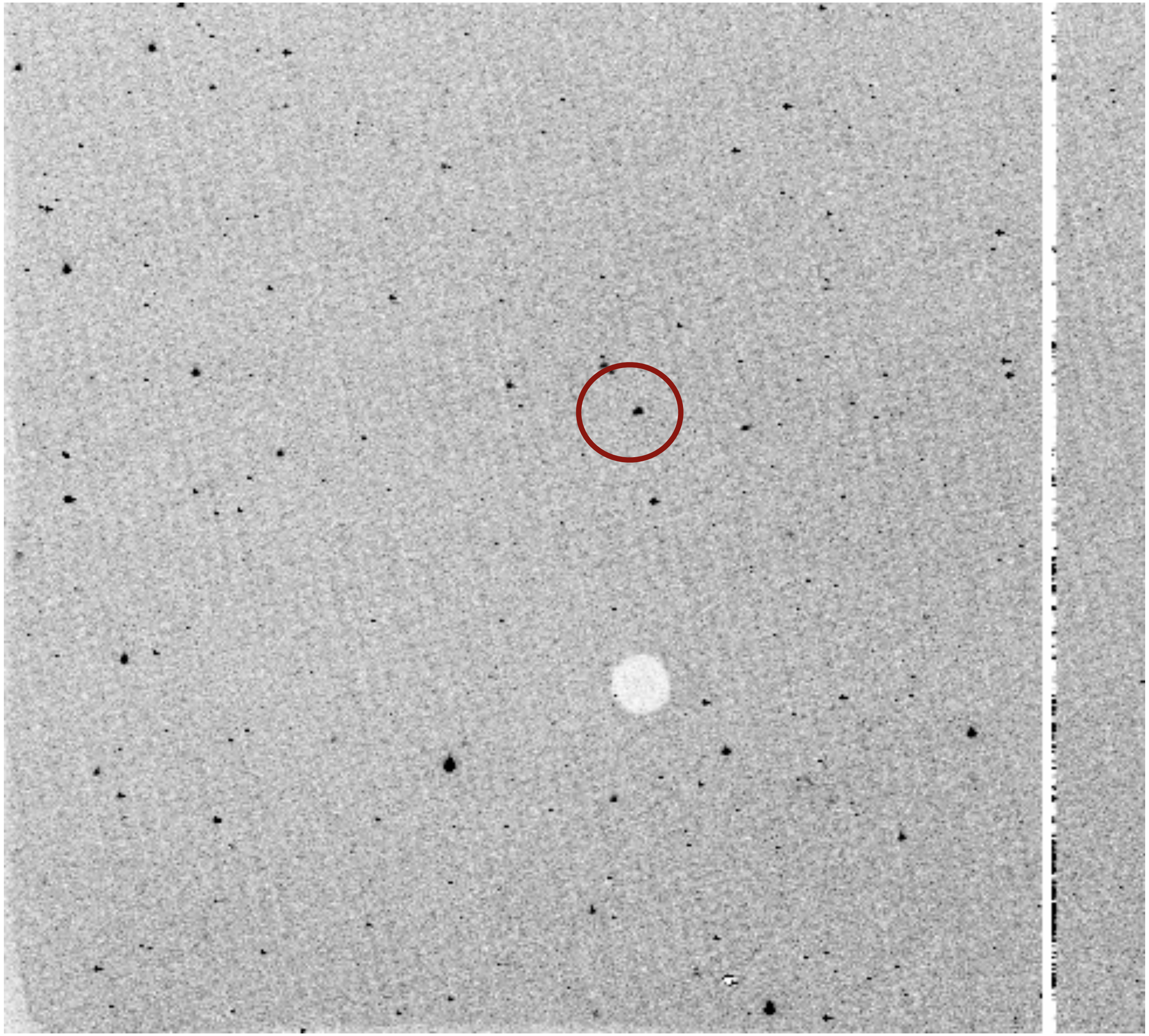


Herbig G. H., 1977, AJ., 217, 693

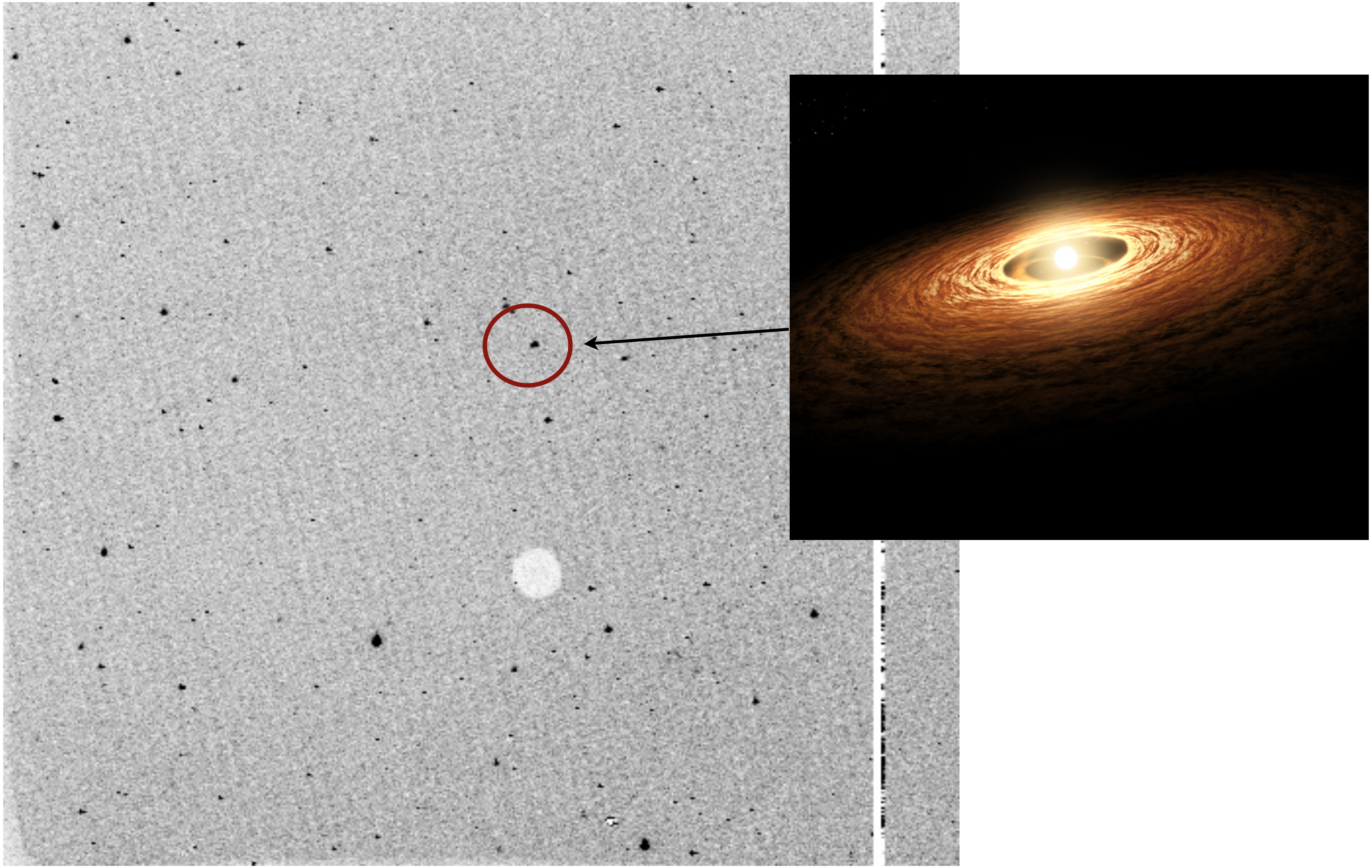
EX Lupi



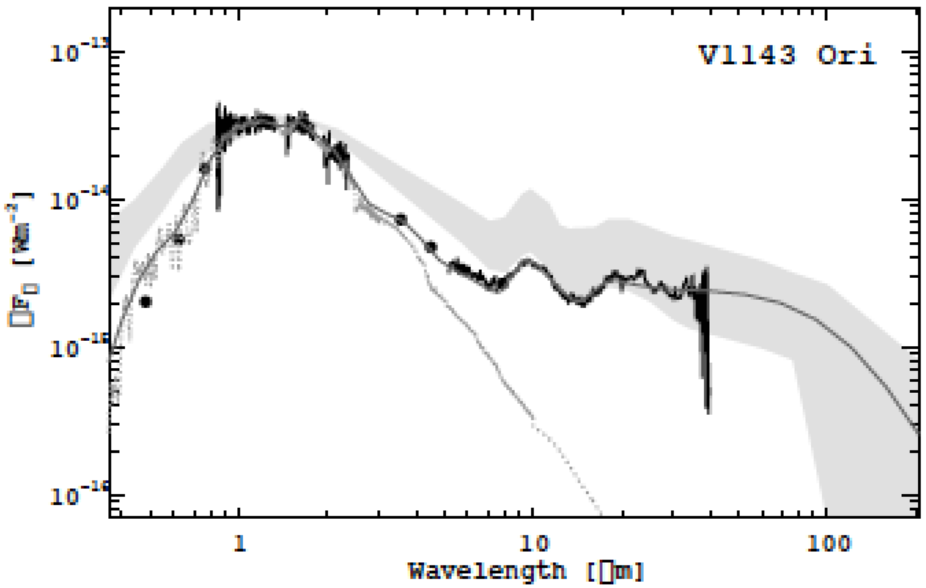
EX Lupi

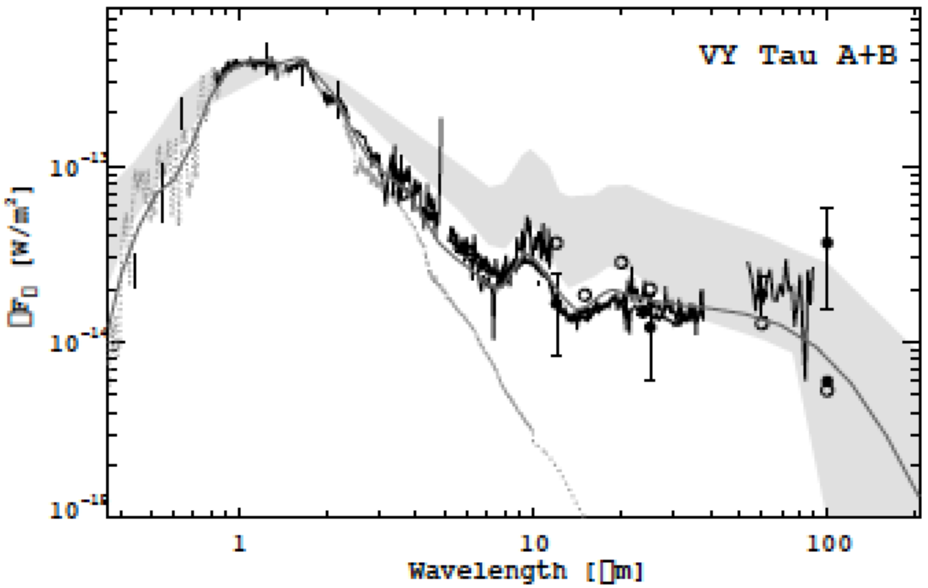


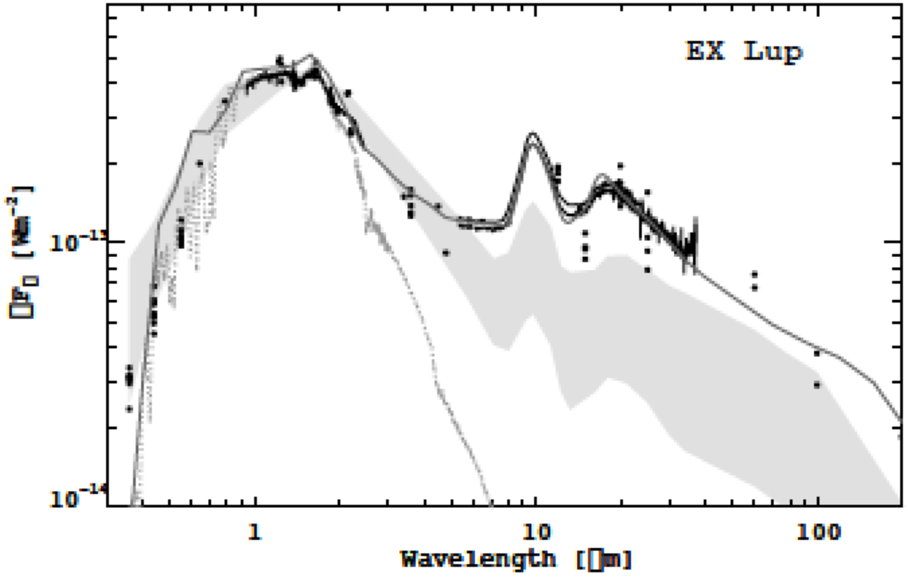
EX Lupi



SEDs of EXors



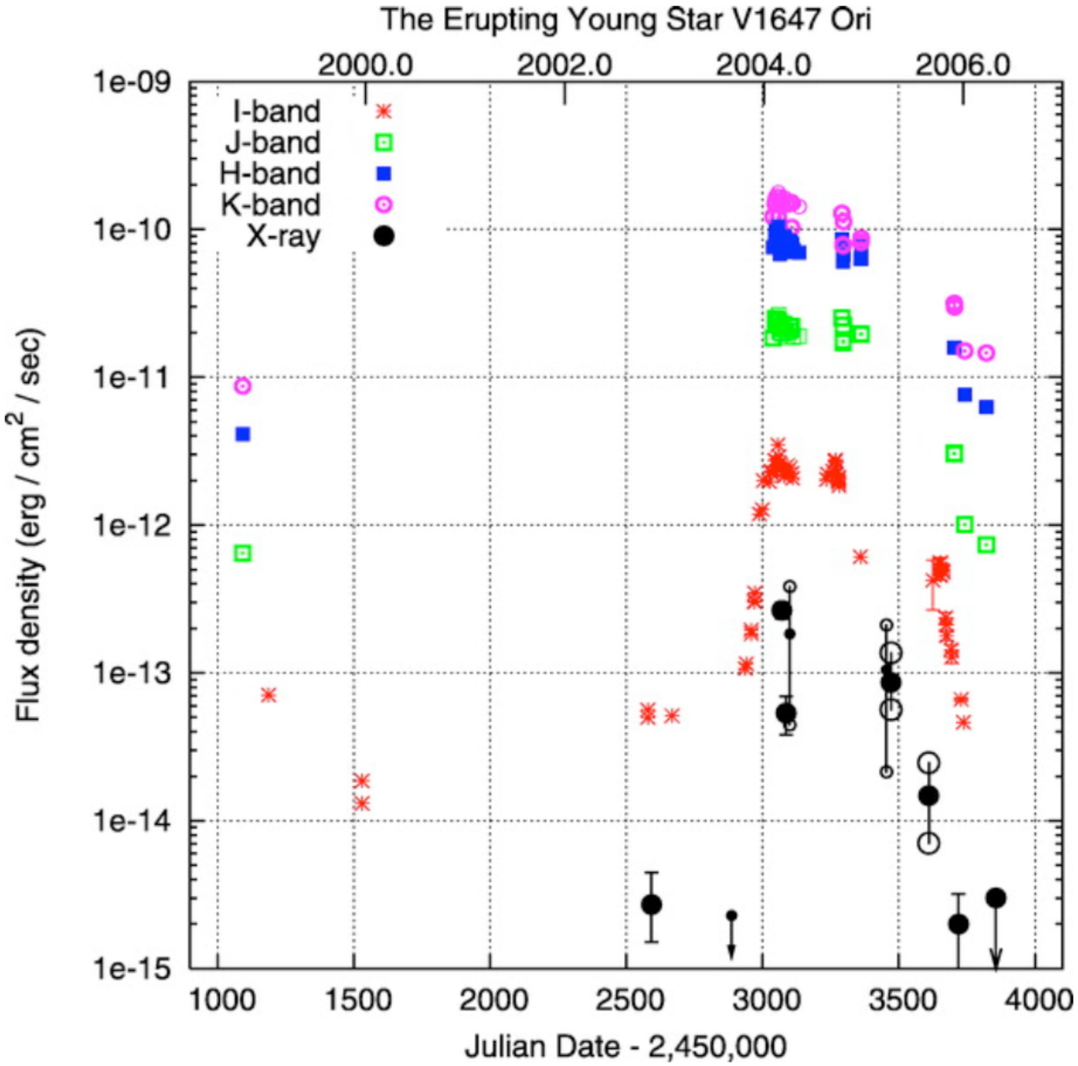




Sipos & Kóspál (in prep.)

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	$> 10^{-6} - 10^{-4}\ M_\odot\ \mathrm{yr}^{-1}$	$10^{-7} - 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$
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

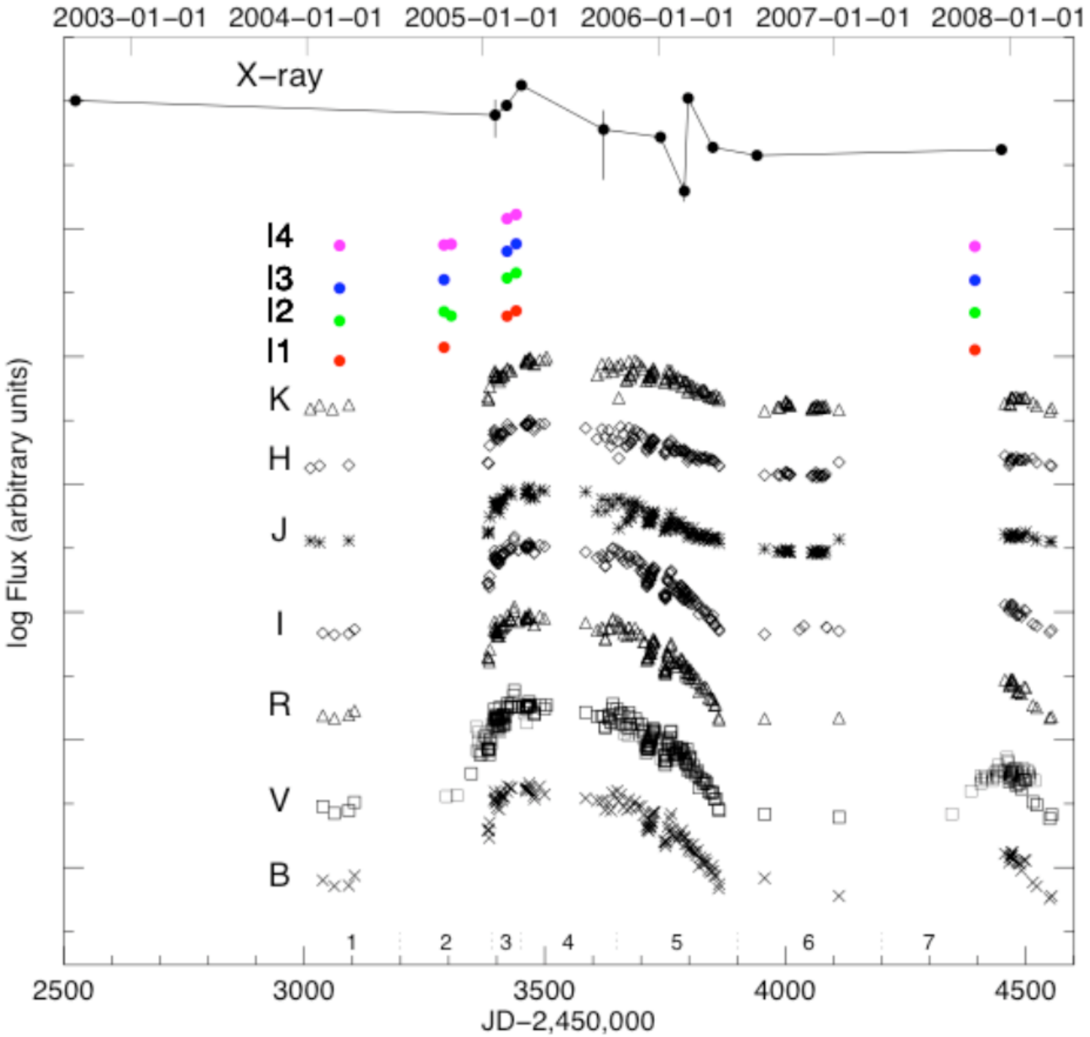
Can X-rays Distinguish Between EXors and FUors?
Do X-rays follow accretion processes?



Kastner et al 2006, ApJ 648, L43

For V1647 Ori, yes

…. But not for V1118 Ori

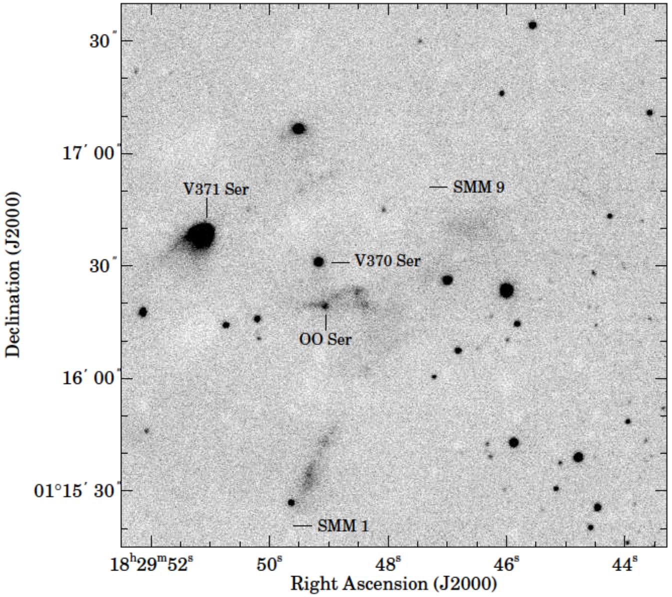


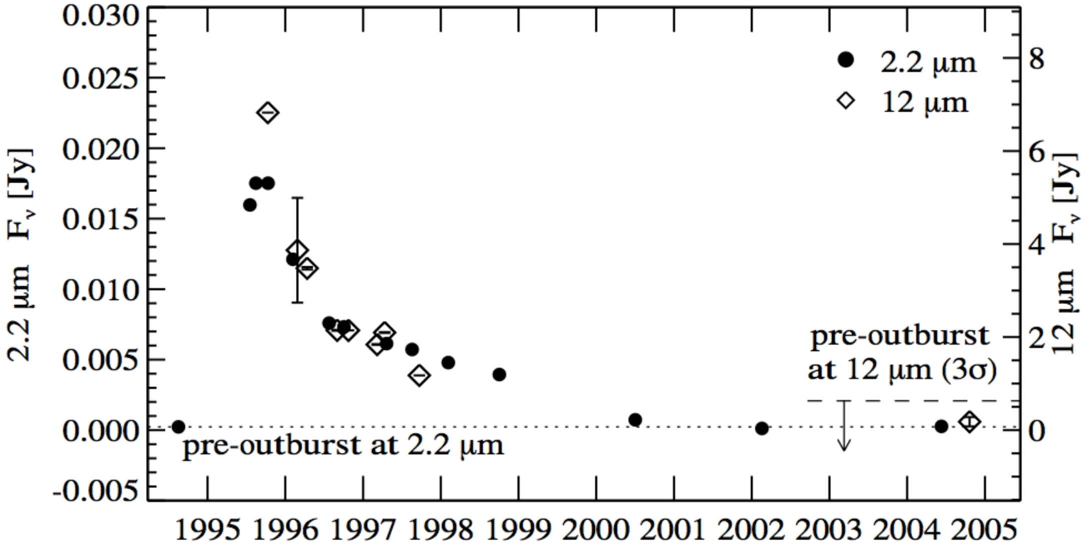
Weak correlation between X-ray and IR (also for EX Lup)

Audard M. et al. (2005) AJ, 635, L81
Audard M. et al. (2010) A&A, 511, A63

At least *some* (soft) X-rays in EXors arise in accretion shocks
Grosso et al. 2010, A&A 522, A56

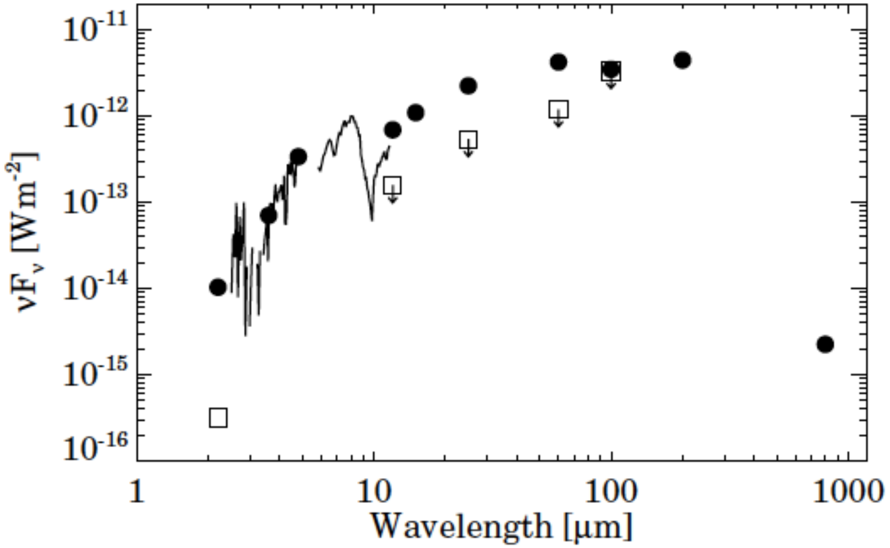
OO Serpentis (1995-2002)





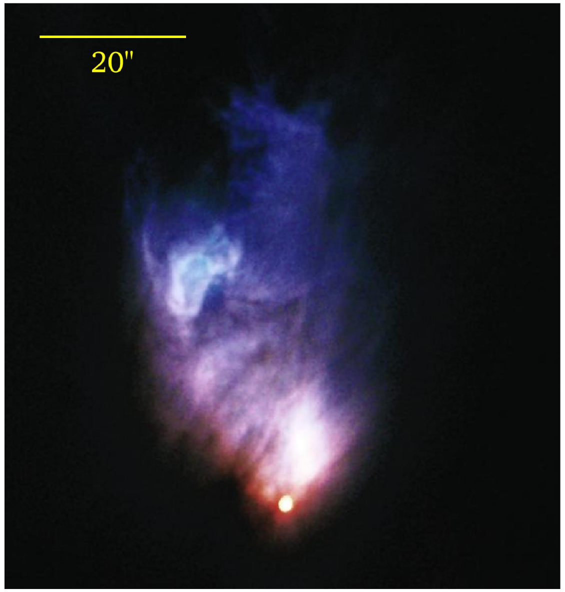
Embedded source, optically invisible

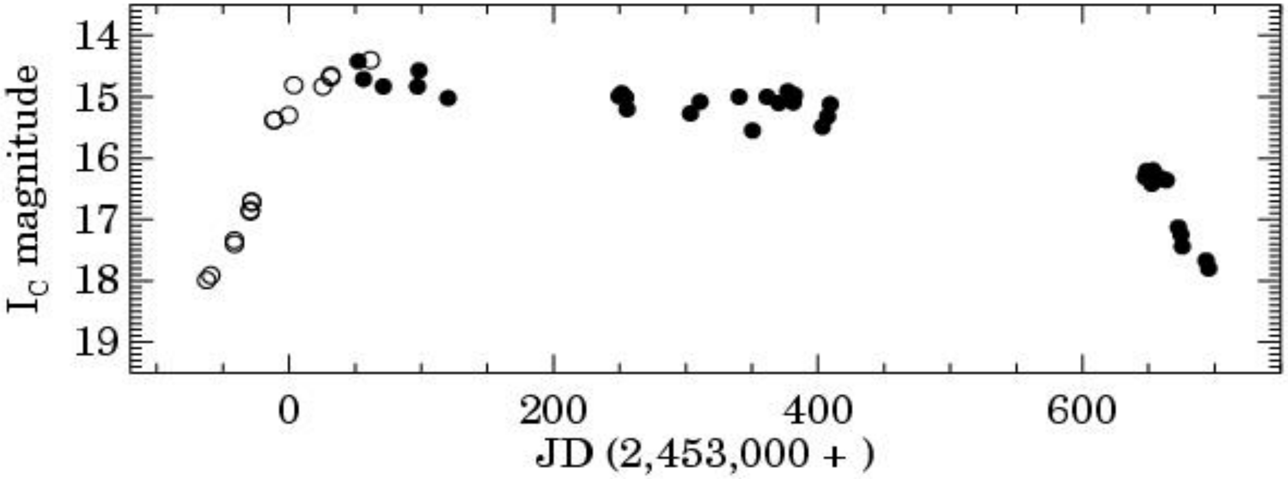
Outburst is *longer* than typical for EXors and *shorter* than typical for FUors



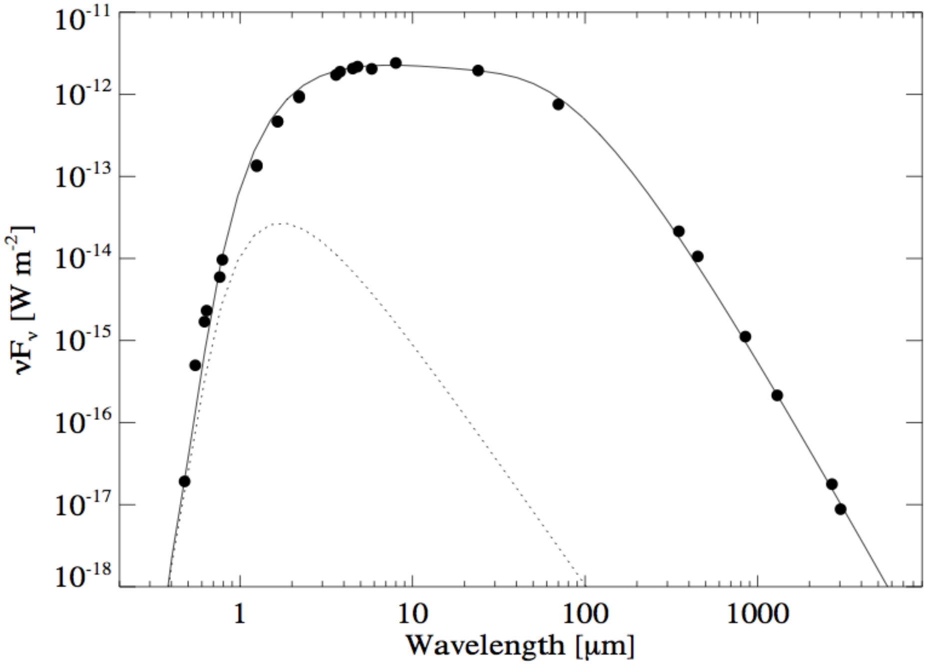
Kóspál et al. (2007)

V1647 Ori (2004-2006)



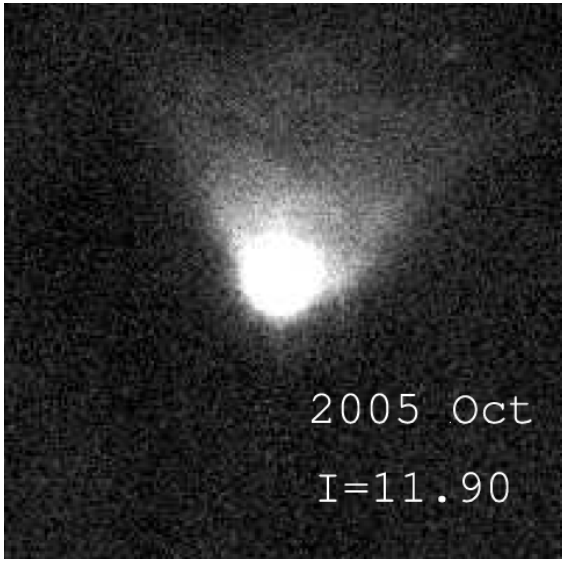


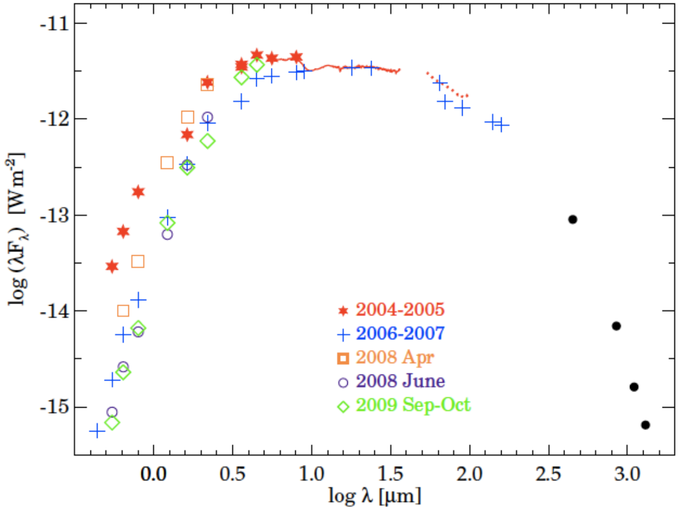
Acosta-Pulido et al. (2007)

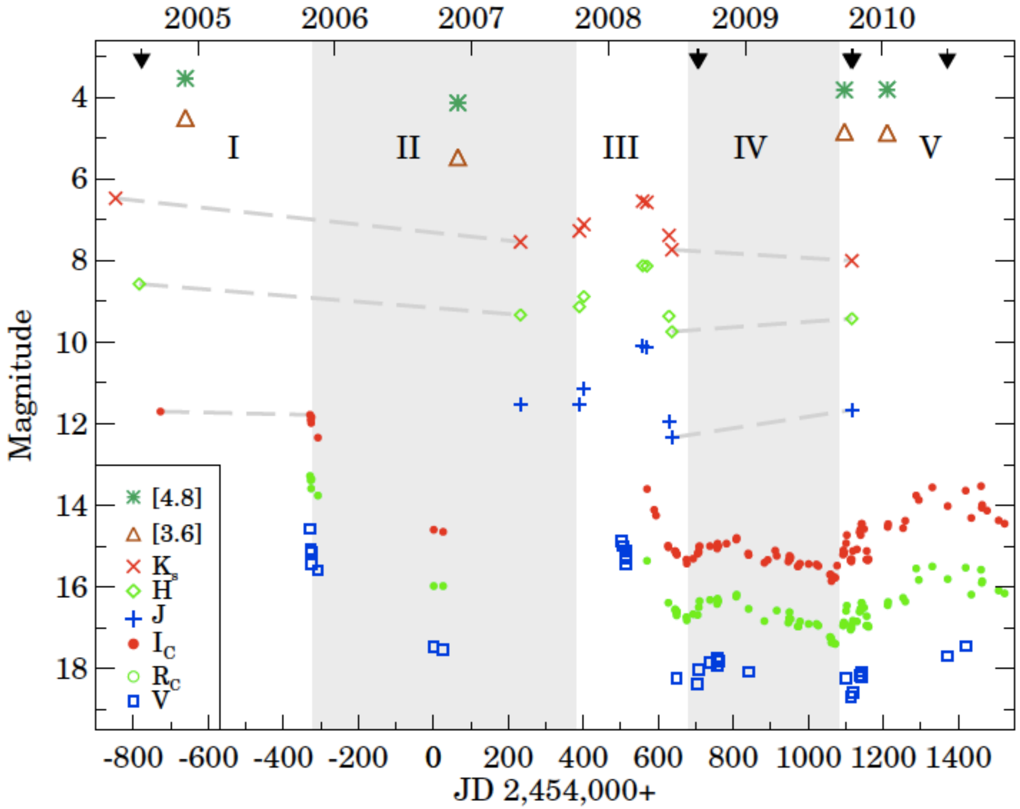


- McNeil Nebula
- It was a “superstar” (many fans)
- recurrent outburst

PV Cep (< 2006)

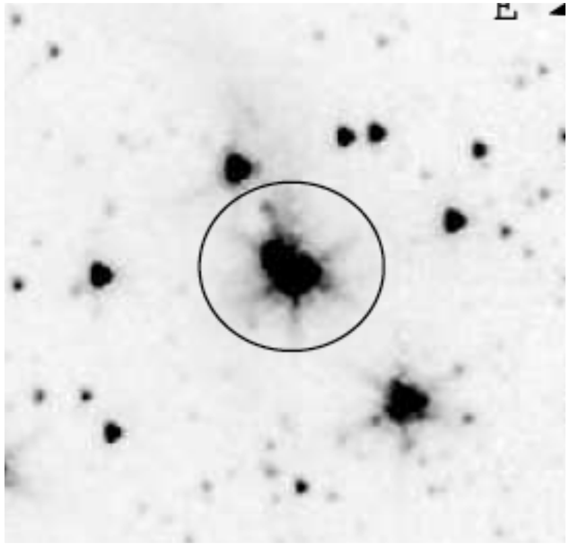


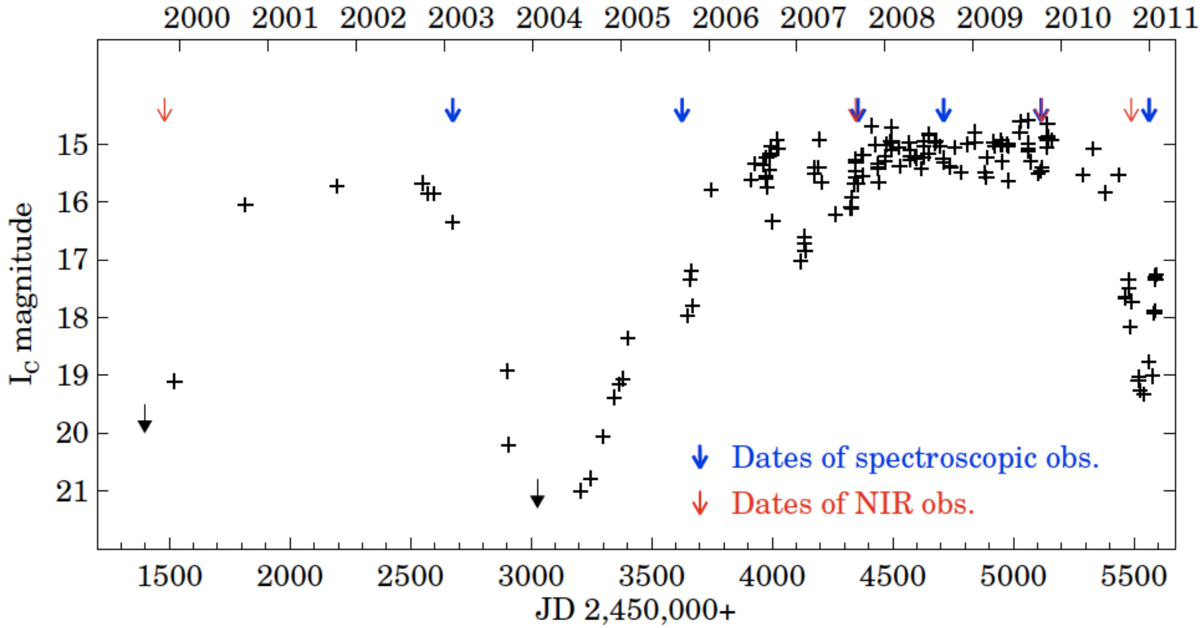


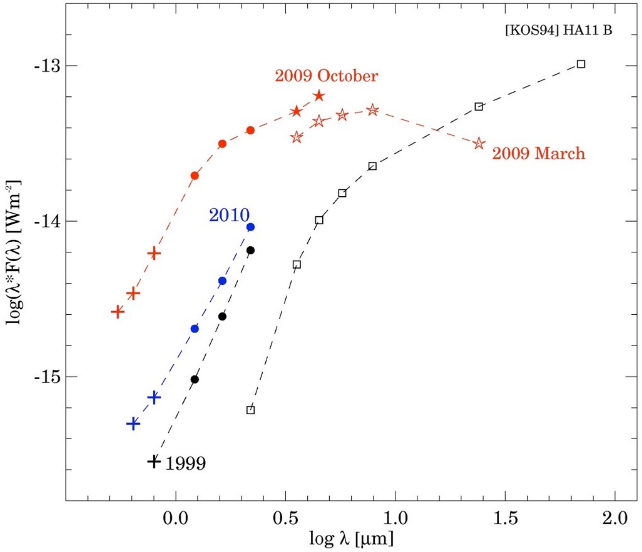


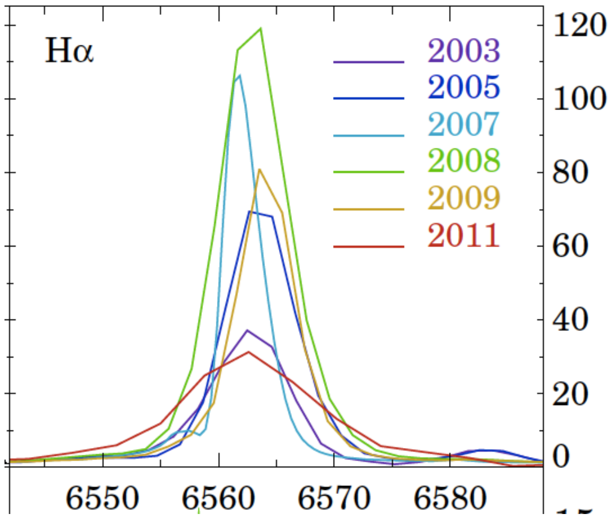
Kun et al. (2011)

[KOS94] Ha 11 (2006-2010)



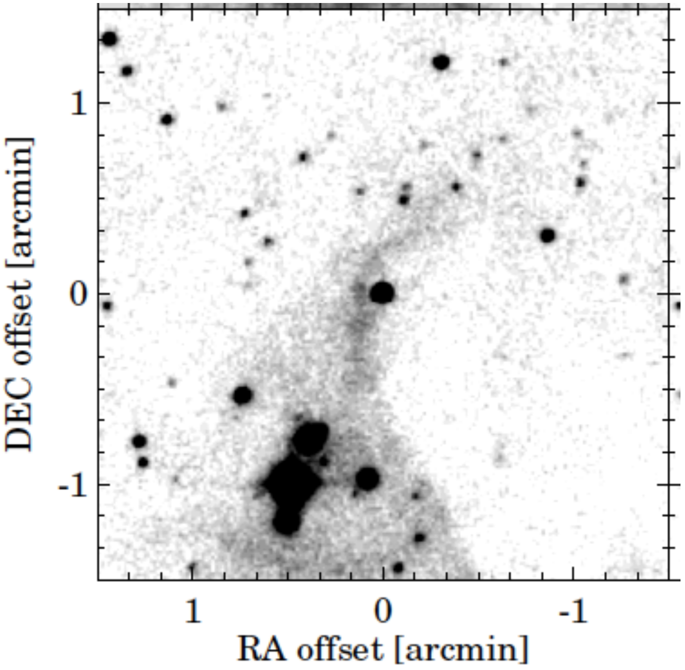


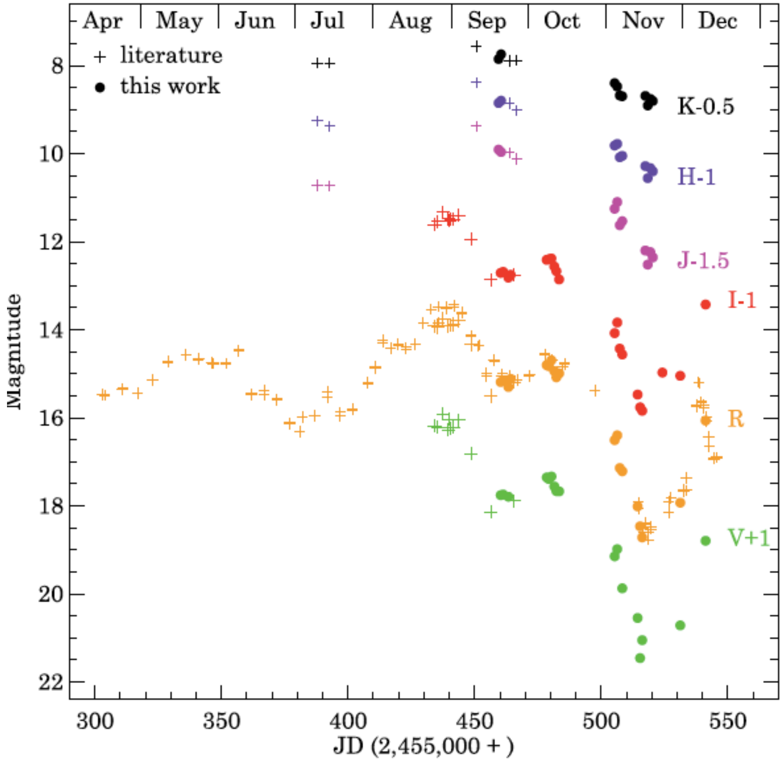




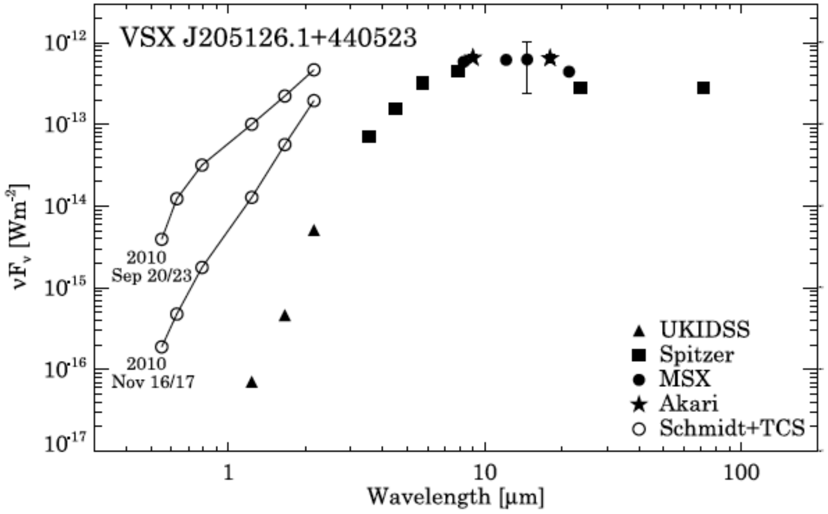
Kun et al. (2011)

V2492 Cyg

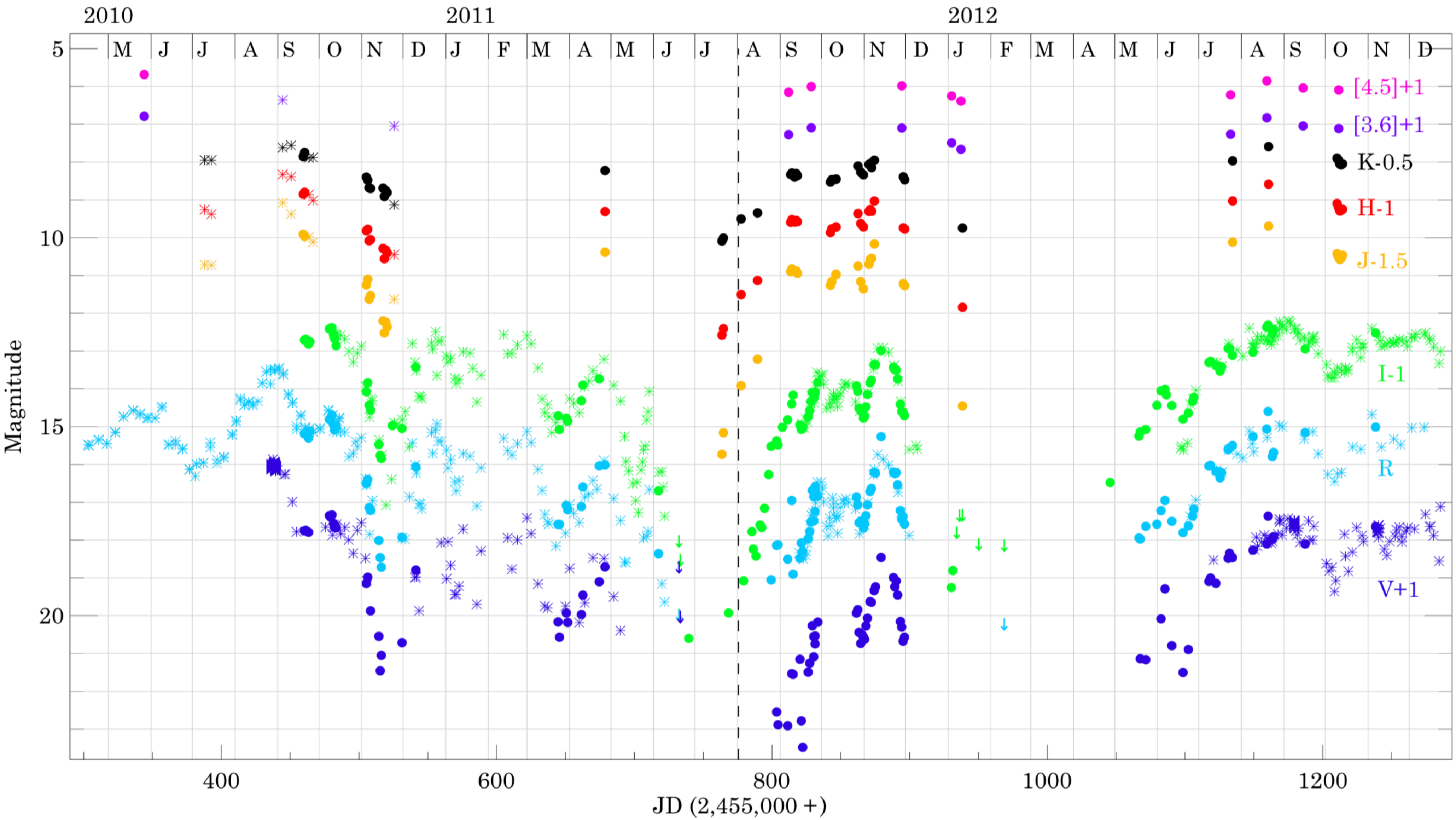




Kóspál et al. (2011)

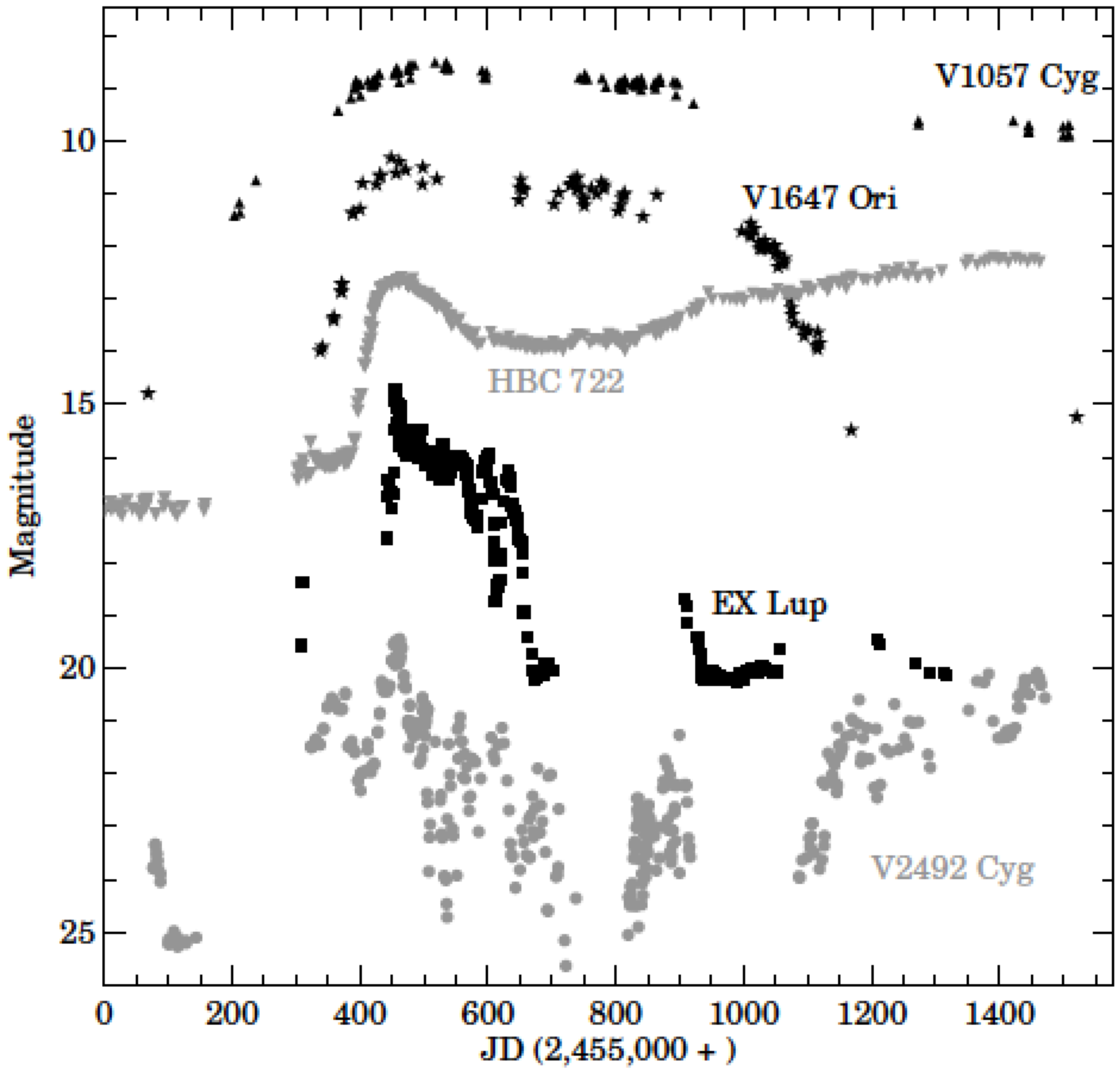


V2492 Cyg

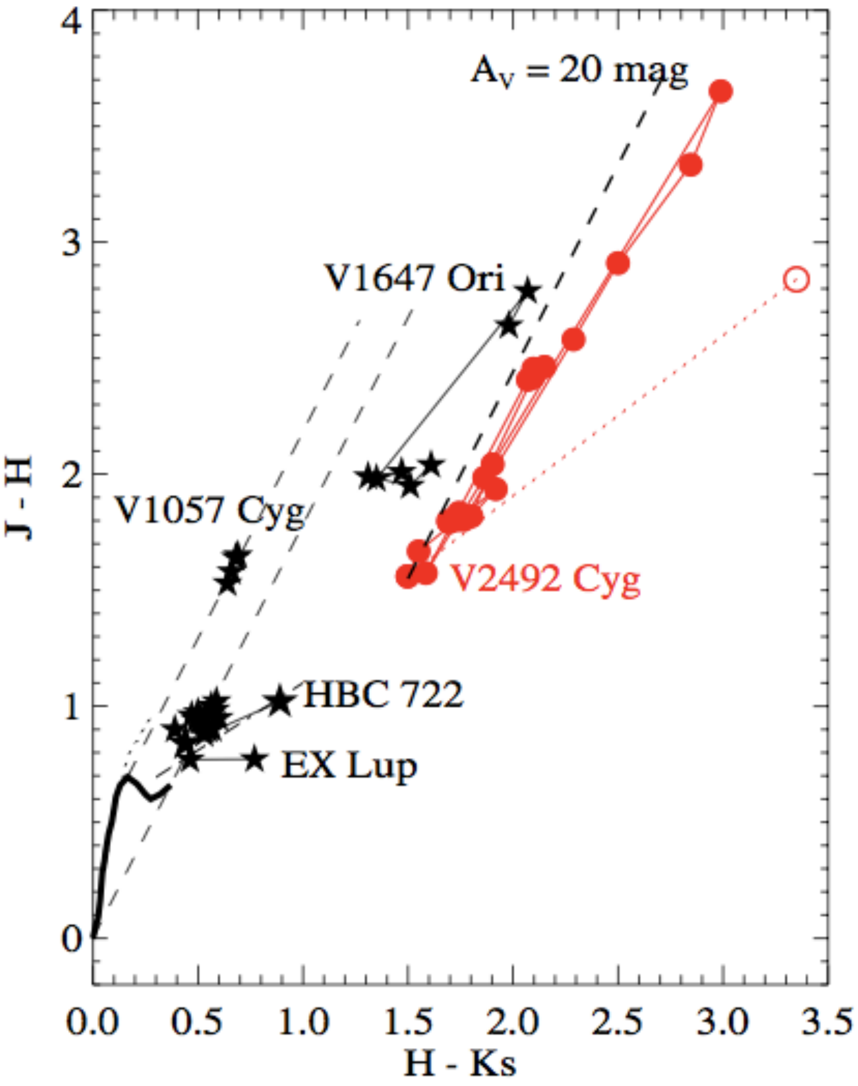


Kóspál et al. (2013)

Comparison of light curves



Colour-magnitude diagram



I. A possible third class of young eruptive stars?

Name	Outburst	Luminosity	Accretion rate
OO Ser	~7 yrs	<8 / 31 L_{sun}	? / ?
V1647 Ori	~2 yrs	5.6 / 44 L_{sun}	$5x10^{-7}$ / $5x10^{-6}$
PV Cep	>1 yrs	40 / 80 L_{sun}	$2.6x10^{-6}$ / $5.2x10^{-6}$
[KOS94] Ha 11	~5 yrs	? / ?	$1.4x10^{-8}$ / $1.6x10^{-7}$
V2492 Cyg	on-going	15/22 L_{sun}	? / $2.5x10^{-7}$

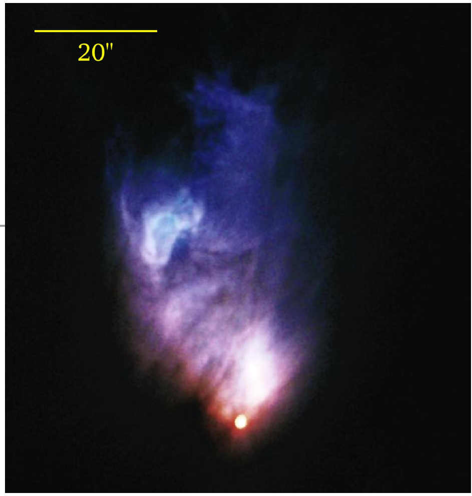
A possible third class of young eruptive stars?

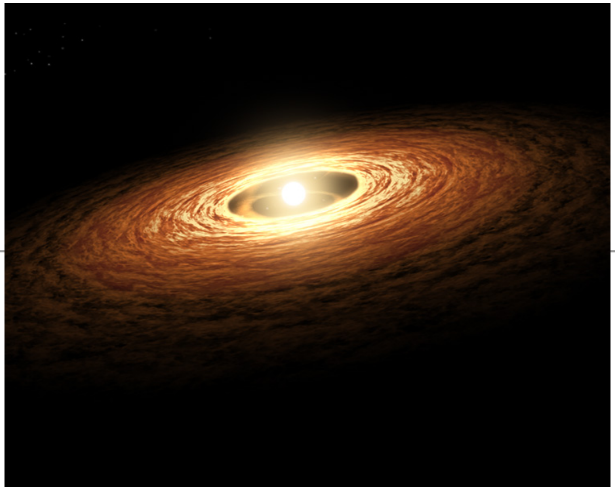
- These objects virtually connect the FUor and EXor classes in terms of outburst length, luminosity, and accretion rate
- Their spectra resemble those of the EXors
- Their circumstellar structure resembles those of FUors (envelope)
- Evolutionary stage: very young objects
- Naming: V1647 Ori-type objects?

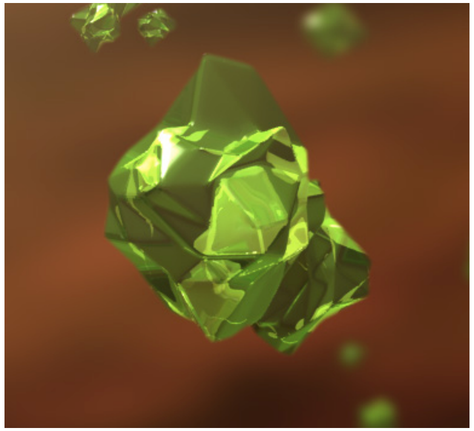
Evolutionary stage

- “Intermediate class”: look very embedded very young sources
- FUors: accretion disk + envelope, but the envelope’s mass and contribution are very different among FUor sources (FU Ori has a small envelope). Claims: could represent the Class I/Class II boundary (Flat sources) where the envelope is dispersed.
- EXors: In quiescence they look as normal T Tauri stars, without any envelope.

Episodic accretion phenomena in the Solar Nebula?

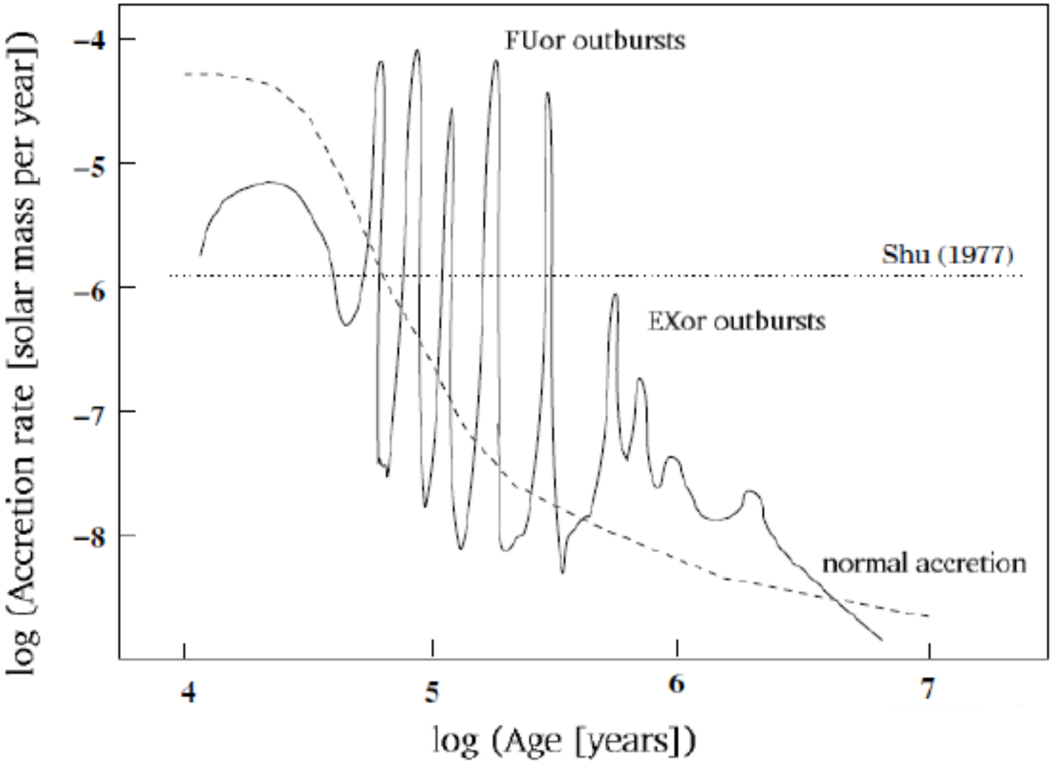




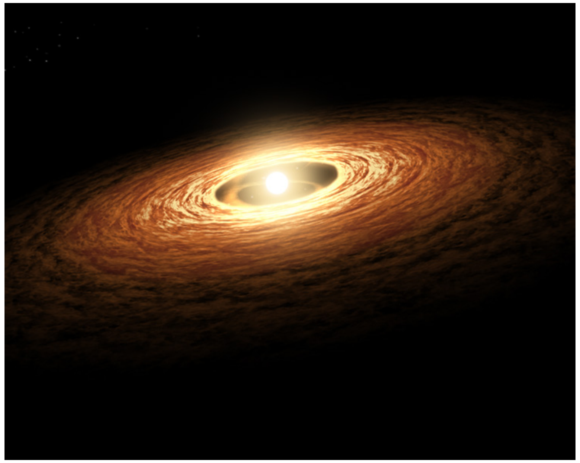


The accretion history of circumstellar disks

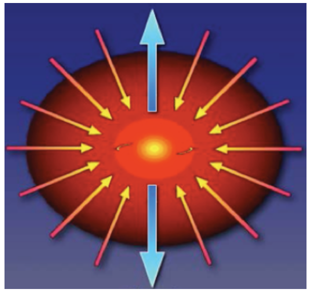
- The general monotonic dropping trend of the accretion rate is punctuated by flare-ups
- The outbursts are confined to the first few million years, and their amplitude decreases
- The outburst is confined to the inner disk (r < 1 AU)
- **This is the site and time of terrestrial planet formation!!!**



Credit: Schulz et al. (2005)



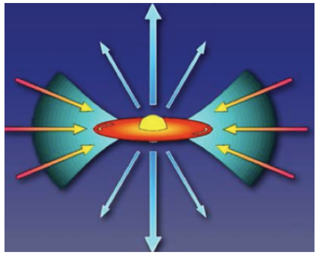
Chronology of planet formation



Molecular clouds and unstable cores
(Blitz *et al.* 2006; Alves *et al.* 2001)

Embedded protostars

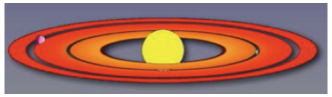
Jets and outflows common
(Bally *et al.* 2006; Ray *et al.* 2006)



Massive accretion disks

Taurus–Auriga (age spread) 0–4 Myr
Radial disk structures and gaps detected

IC 348 and Chamaeleon I star-forming regions
2 Myr, warm dust disks around ~50–65% of stars
(Luhman 2008)



Low-mass disks with evolved dust

Upper Scorpius Association
(5 ± 3 Myr, iso: Slesnick *et al.* 2008)

Warm dust around ~10% of young stars
Eta Cha association
(12 ± 6 Myr, Li: Mentuch *et al.* 2008)
TW Hya associations
(12 ± 8 Myr, Li: Mentuch *et al.* 2008;
8 ± 1 Myr, dyn: de la Reza *et al.* 2006)

[Myr]

$T_0 - 1$: Supernova injects radionuclides
^{26}Al, ^{36}Cl, ^{41}Ca, ^{53}Mn, ^{60}Fe initial SS abundances
(Oulette *et al.* 2007; Mostefaoui *et al.* 2005)

0

T_0: Earliest CAI formation
Pb–Pb ages of Efremovka CAIs: 4567.2 ± 0.6 Ma
(Amelin *et al.* 2002)

$T_0 + 0.1$: Latest CAI formation
Pb–Pb ages of Allende CAIs: 4567.1 ± 0.2 Ma
(Connelly *et al.* 2008)

0.5

1

$T_0 + 1$: Formation of magmatic iron meteorites
^{182}Hf: 1.5 ± 0.2 Myr younger than CAI
(Bizzaro *et al.* 2005; Qin *et al.* 2008)

$T_0 + 2$: Peak of chondrule formation
^{26}Al: 2 ± 1 Myr younger than CAI (Kita *et al.* 2005)
Pb–Pb of Acfer 094 chondrules: 4564.7 ± 0.6 Ma (Amelin *et al.* 2002)

$T_0 + 3$: Formation of basaltic eucrites (Asteroid Vesta)
^{26}Al: 3.1 ± 0.2 Myr younger than CAI
(Bizzaro *et al.* 2005)

$T_0 + 4$: Latest chondrule formation
Pb–Pb ages of CB chondrite chondrules: 4562.8 ± 0.9 Ma
(Krot *et al.* 2005)

5

10

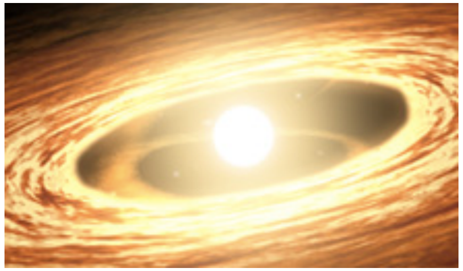
$T_0 + 10$: Formation of basaltic angrites
Pb–Pb: 4558.6 ± 0.2 Ma (Amelin 2007)

Apai & Lauretta (2010)

The effects of eruptions on the disk I.

Material in the outbursting region (r < 0.3 AU)

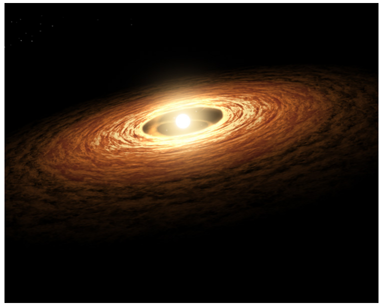
- Cyclic density distribution in the inner disk (pile up - drain - pile up)
- Effect of stellar/substellar companion in the inner disk(?)
- Expanding ionization front
- Evaporation of dust grains and partial erosion of larger planetesimals (can planetesimals form in this region at all?)
- Temporarily increased turbulence (removal of angular momentum)
- Radial and vertical flows, high speed motions
- Gas chemistry at high temperature
- Accretion of the freshly created material onto the star
- Or could fresh material escape via stellar wind?



The effects of eruptions on the disk II.

Material outside the outburst region

- Affected mainly via increased irradiation by the central region
- Evaporation of dust particles, and partially also of larger bodies
- Rearrangement of the density structure, changing extinction
- Chemical, mineralogical processes which require short time
- Chondrules may be formed at larger distances and at later times
- Snowline moves temporarily further out
- **The spectrum of the radiation field becomes “harder”**
- Dissociation of molecules (isotopically selective photodissociation)
- Mineralogical changes in dust grains

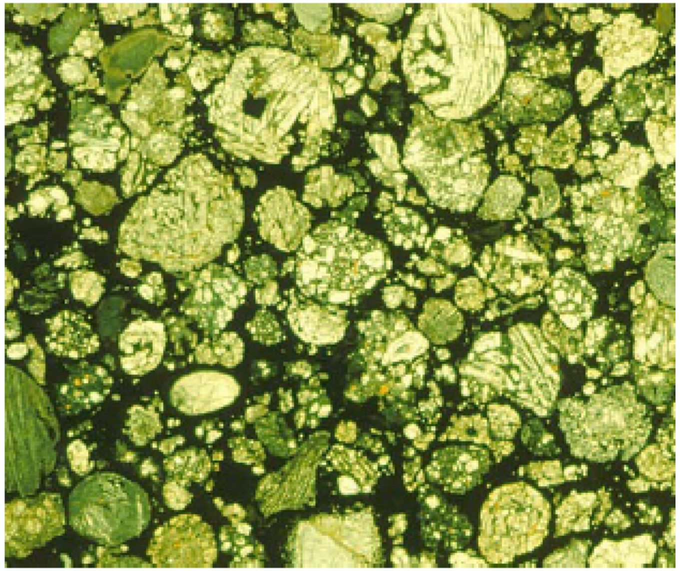


Outbursts in the Solar Nebula?

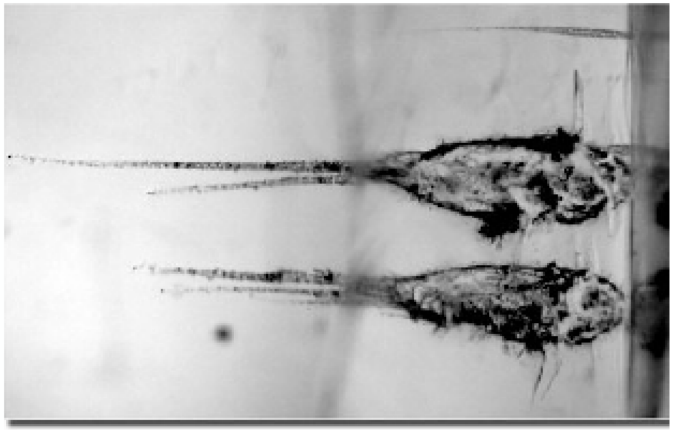
- All T Tau stars undergo outbursts? Are FUors/EXors similar to normal TTau stars?
- Not sure: depends on the outburst mechanism (if companion is needed...)
- **Is there any evidence in meteoritic samples?**
- Is there any evidence for a hot phase of the solar nebula?
- Several chondritic groups abundance patterns of volatile elements suggest a slowly cooling nebula. Some groups of iron meteorites fractionated prior the formation of their parent bodies. Picture of a widespread condensation from a hot nebula.
- Is there any evidence for short episodes of outburst?
- Possibly the diversity of meteorite groups. Models that cool down between outbursts richer context for meteoritic diversity.
- High temperature formation of material at unusually late dates? Age groups?

Thermal processing in the SS

- Chondrules (once molten silicate spherules) and CAIs are delivered to the Earth from the cold Asteroid Belt (~180 K) by primitive chondritic meteorites.
- Stardust mission: sample returned from comet Wild 2 contained crystalline silicates.
- Did they form in situ?
- Were they mixed outward from the hot inner disk?



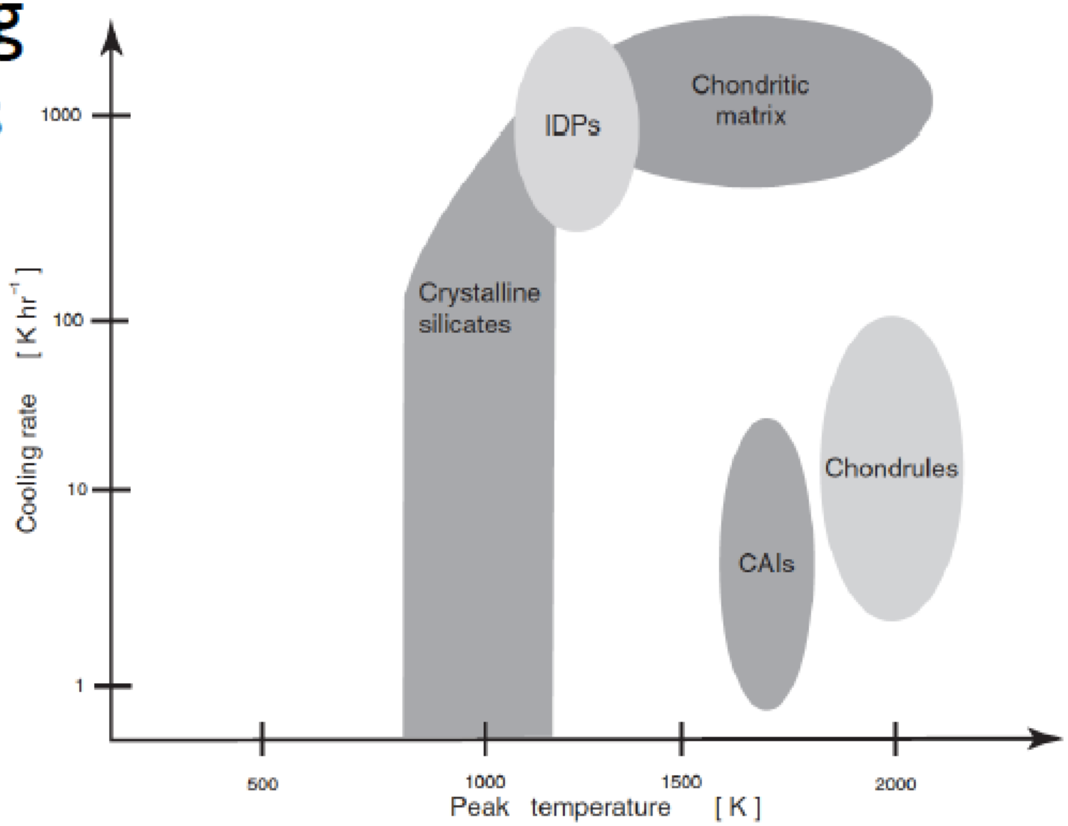
Semarkona meteorite
http://meteorite.unm.edu



Stardust impact tracks
NASA/JPL

Thermal processing in the SS

- Most of the primitive material in the Solar System (e.g. chondrules and some CAIs) shows evidence for multiple transient heating events.
- They were formed in a transient high-temperature heating event (initial melting needed 2200 K for minutes to seconds)
- Multiple transient heating events afterwards of various intensity (peak temperatures of 1300−1500 K for hours to days)



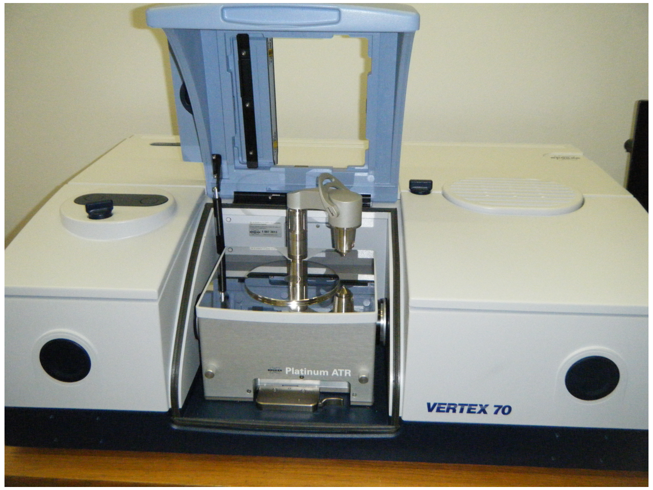
Apai et al. (2010)

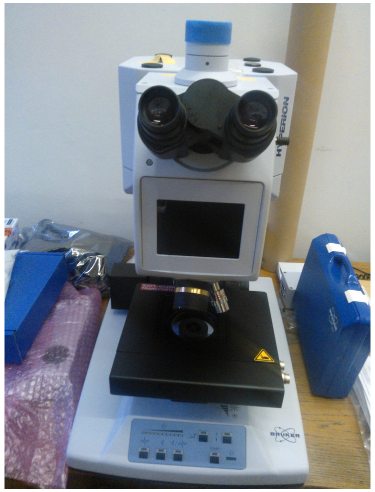
Outbursts in the early SS?

- Possible heating mechanisms:
  - Shock waves, X-ray flares, X-wind, lightning, impacts
  - Episodic outbursts like in EX Lup?
- Argument against accretion outbursts: the hot phase is too long
- But: outburst light curves often show short peaks
- Combination: if outbursts are caused by the formation and infall of large clumps in the disk, these may generate shock waves while migrating inwards
- We need to study outbursts with better time and spatial resolution

A group in CSFK

- As of 2012 January 1, four research institutes of the Hungarian Academy of Sciences - astronomy, geochemistry, geodesy and geophysics, geography - merged into a new research centre.
- Laboratory astrophysics project just started
- Bruker Vertex 70 FTIR spectrometer with Bruker Hyperion 2000 FTIR microscope





- Meteoritic research

Kabai meteorite, CV3 carbonaceous chondrite