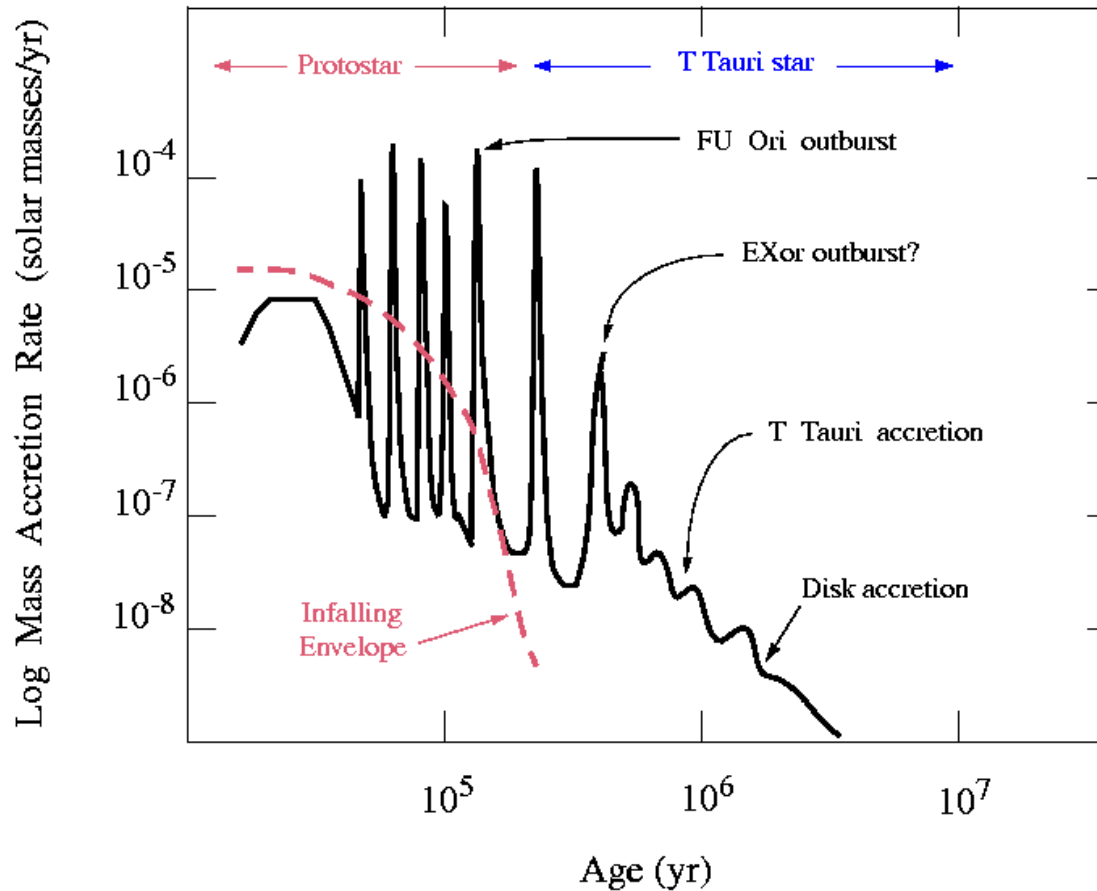


Problems of protostellar accretion

- **When is the protostellar mass accreted?**
 - Class 0 phase? Class I phase??
 - FU Ori objects (0, I)? Or other outbursts?
 - embedded objects \Rightarrow (FIR) luminosities?
- SOFIA: spatially-resolved MIR-FIR images:
 - (FIR) luminosities in crowded regions, binaries, differentiate envelope vs. environment
 - emission lines \Rightarrow protostellar accretion tests?

FU Ori and protostellar accretion

When is mass accreted? Early rapid phase (Class 0) or in short FU-Ori like outbursts in Class I? (Or both?)



The accretion (luminosity) problem

- When is the stellar mass accreted?

$$L(\text{acc}) \approx (GM_*/R_*)dM/dt ;$$

with $(M_*/R_*) \approx 0.17 M_\odot$ ($T_c \sim 10^6$ K, D fusion),

$$L(\text{acc}) \approx 52 L_\odot (dM/dt / 10^{-5} M_\odot/\text{yr})$$

- Taurus: $dM/dt \approx 2-4 \times 10^{-6} M_\odot/\text{yr}$;

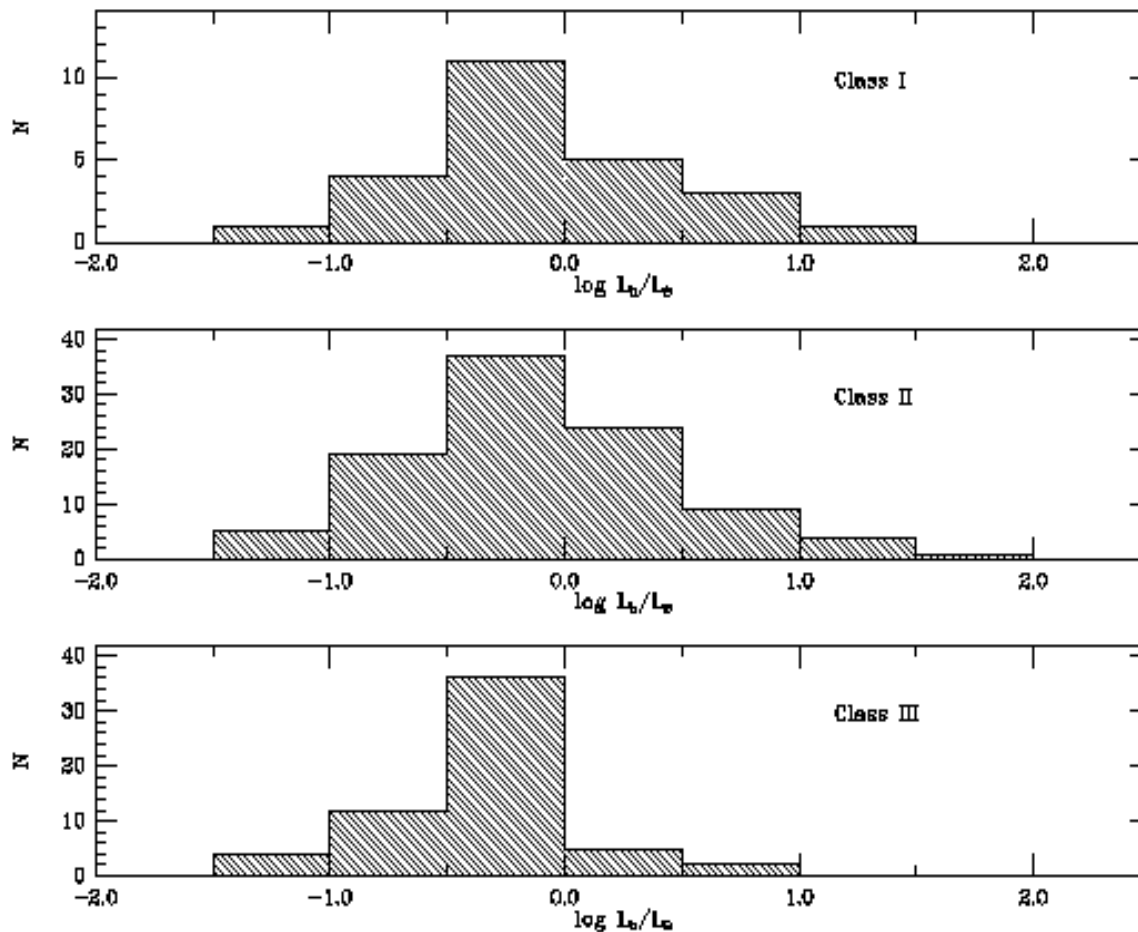
predict $L(\text{acc}) \approx 10 - 20 L_\odot$;

but $\langle L \rangle$ (total, observed) (Class I) $\approx 0.5 L_\odot$!

The accretion (luminosity) problem

Taurus: dM/dt (infall) $\approx 2-4 \times 10^{-6} M_{\odot}/\text{yr}$ (SEDs; ALS, KCH)

predict $L(\text{acc}) \approx 10-20 L_{\odot}$; $\langle L \rangle$ (observed) $\approx 0.5 L_{\odot} \approx L_{*}$!



The accretion (luminosity) problem

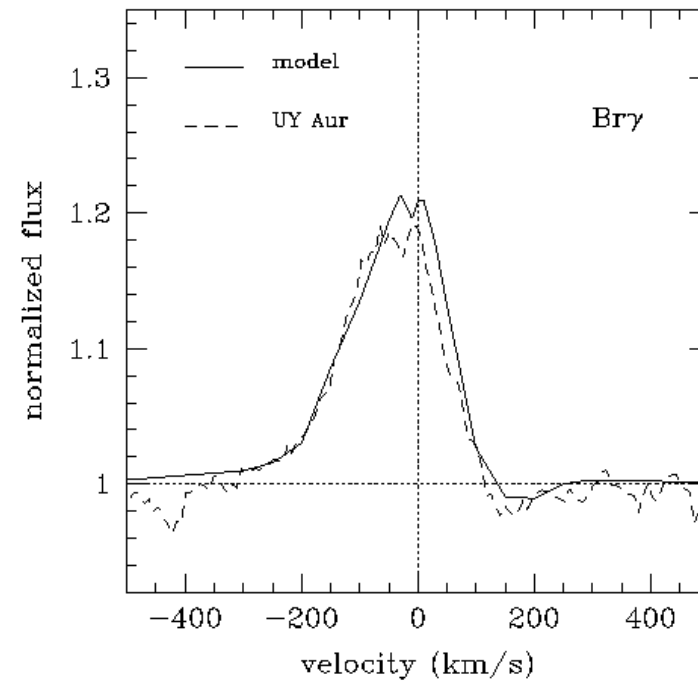
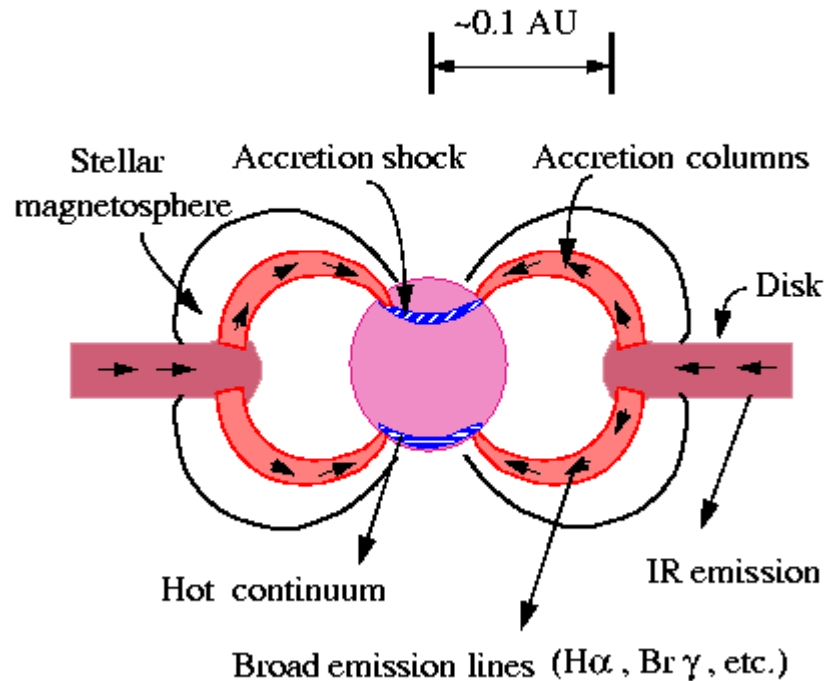
- Solution 1: $R_* \gg R(\text{birthline})$?
 - Reduces $L(\text{acc}) \sim GM_* dM/dt / R_*$
 - $\Rightarrow L_* \propto R_*^2 T^4$ becomes too large unless T very low
 - $\Rightarrow t_{\text{KH}}$ becomes very short - core lifetime too short?
- Magnetospheric infall line profiles for (some) Class I sources can ultimately constrain M_*/R_*
(Muzerolle et al. 1998): emission lines (Br γ)
$$\Delta v \approx (2GM_*/R_*)^{1/2}$$

Are there longer- λ lines for higher- A_V sources?

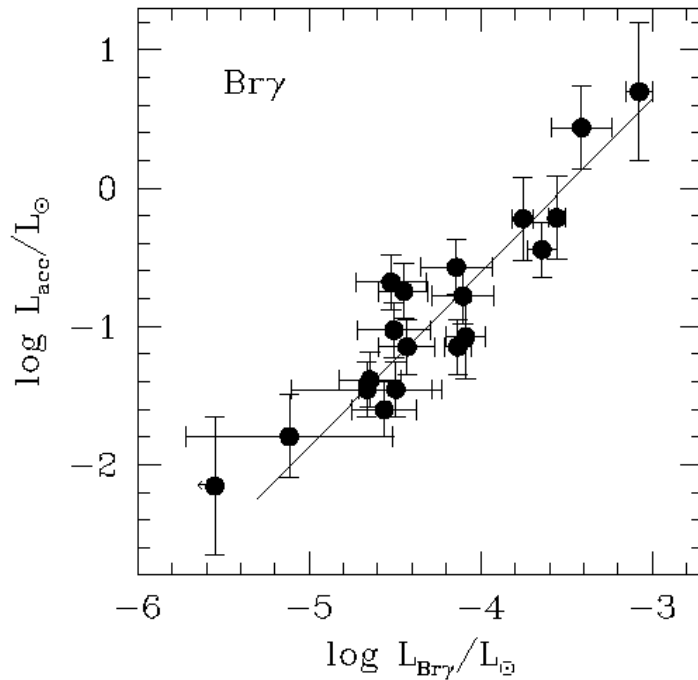
Magnetospheric infall line profiles

(Muzerolle et al. 1998): line width $\approx (2GM_*/R_*)^{1/2}$

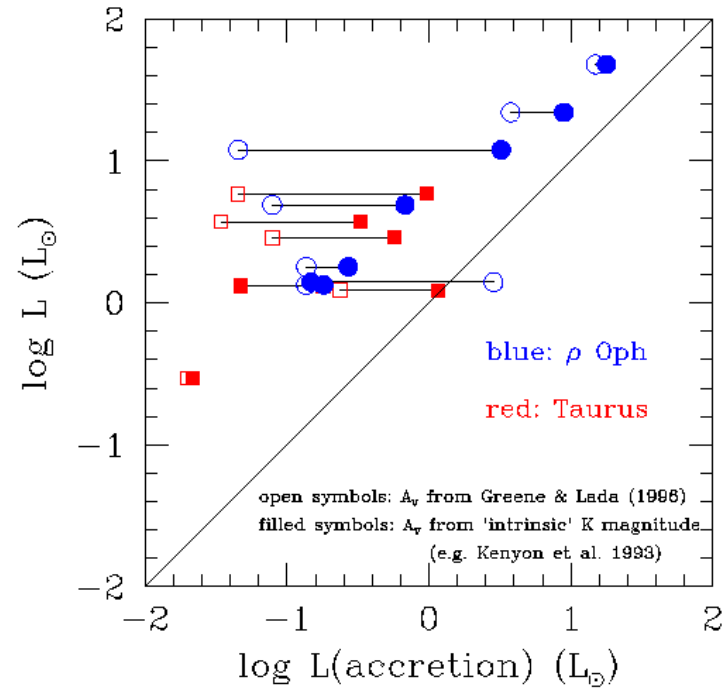
T Tauri star - magnetospheric accretion



$L(\text{Br } \gamma) \propto L(\text{acc})$ (Muzerolle et al. 1998);
 can use to estimate accretion in Class I sources
 longer λ lines for higher A_V sources?



Taurus optical PMS



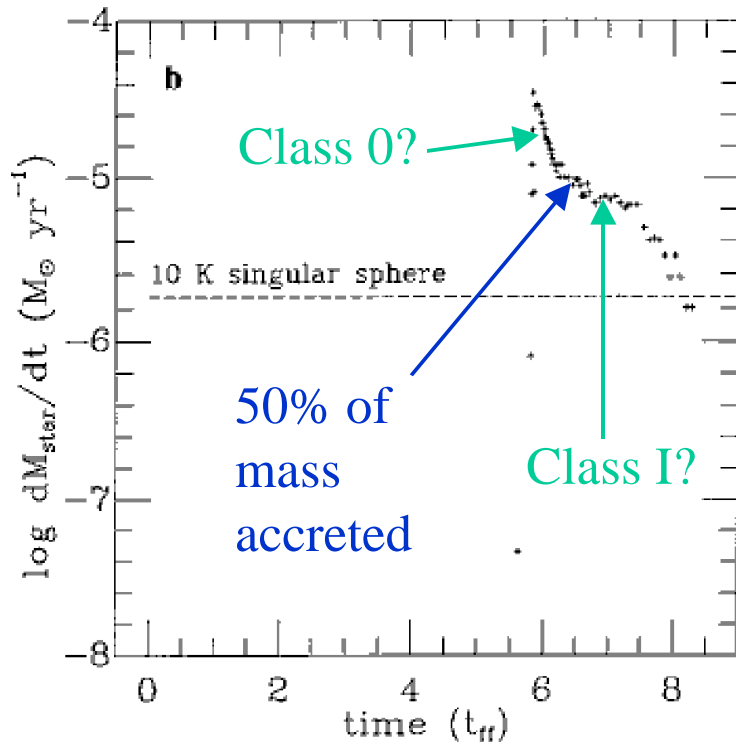
Class I sources

- **Solution 2: accretion during Class 0 phase?**

$dM/dt(\text{infall})$ may be very high in *initial* collapse phase because of flat central density in protostellar core (André et al., Henriksen et al. 1997)

$\rho \propto r^{-2}, \Rightarrow dM/dt \sim \text{constant}$

$\rho \propto \text{constant}, \Rightarrow dM/dt \sim \text{decays with time}$



Problem: hard to get most of the mass to accrete in the early rapid infall phase (cf. *Foster & Chevalier 1993*)

← For example, collapse of a (uniform) sheet \Rightarrow much of mass infalls in ‘plateau phase’ (*Hartmann et al. 1994*)

The accretion (luminosity) problem

- **Solution 2: accretion during Class 0 phase?**

Problem: $dM/dt(\text{infall})$ may be much higher than for Class I sources, $dM/dt \sim 10^{-4} M_{\odot}/\text{yr}$ from SED models (*Jayawardhana et al. 1999*); **but**

$L(\text{total}) \sim 1-10 L_{\odot}$ for many objects \Rightarrow **still have a (worse) luminosity problem! Still need outbursts(?)**

- **external medium vs. infalling envelope? ($T \sim 10-15\text{K}$)**
FIR imaging might help distinguish on 2000 AU scales

Not clear whether Class 0 \rightarrow Class I always, or are collapsing objects in dense environments

The accretion (luminosity) problem

- Solution 3: infall piles up in outer disk, accretion to star in short-lived outbursts?
FU Ori objects ($dM/dt \sim 10^{-4} M_{\odot}/\text{yr}$ for ~ 100 yr)
but statistics consistent with only $\leq 0.1 M_{\odot}$ accreted
 \Rightarrow Are we missing rapidly-accreting objects?
highly-extincted, embedded objects (half of known FUors have large A_V)
Reipurth & Aspin - HH energy sources - ID from CO $2.3\mu\text{m}$ absorption

Protostellar accretion in bursts?

- Need statistics!

Taurus: expect only ~ 1 FU; L1551 IRS5?

(low-L; $dM/dt \sim 4 \times 10^{-6} M_{\odot}/\text{yr}$; Rodriguez et al 1999)

⇒ More distant, larger samples

- SEDs, luminosities in highly-extincted, crowded regions

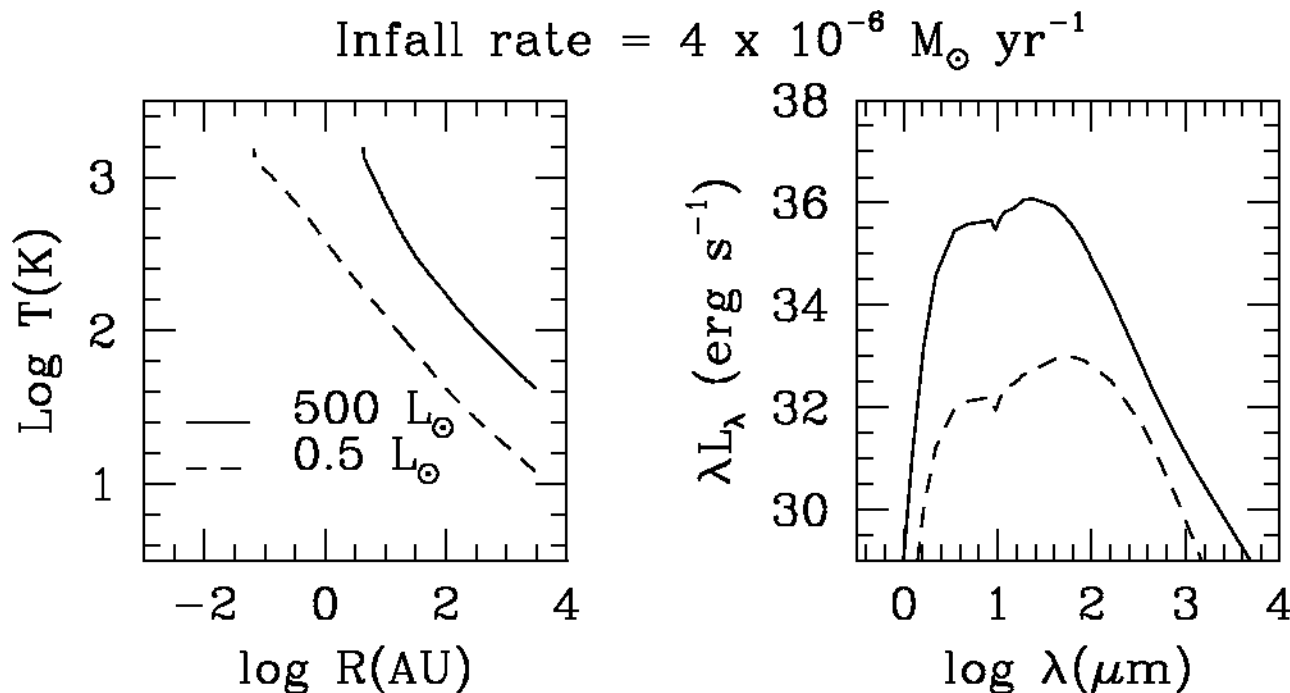
Many regions have several independent objects within ~ 3000 AU $\sim 20''$ in *nearest* regions

- spatial resolution in FIR needed ⇒ SOFIA

- Luminosities, spectral classes of heavily-embedded sources?

Extraction of SEDs from objects in high extinction, crowded regions \Rightarrow **SOFIA MIR & FIR imaging**

Note: luminosity comparison (Class I and Class II) has only been done for Taurus because of crowding, extinction

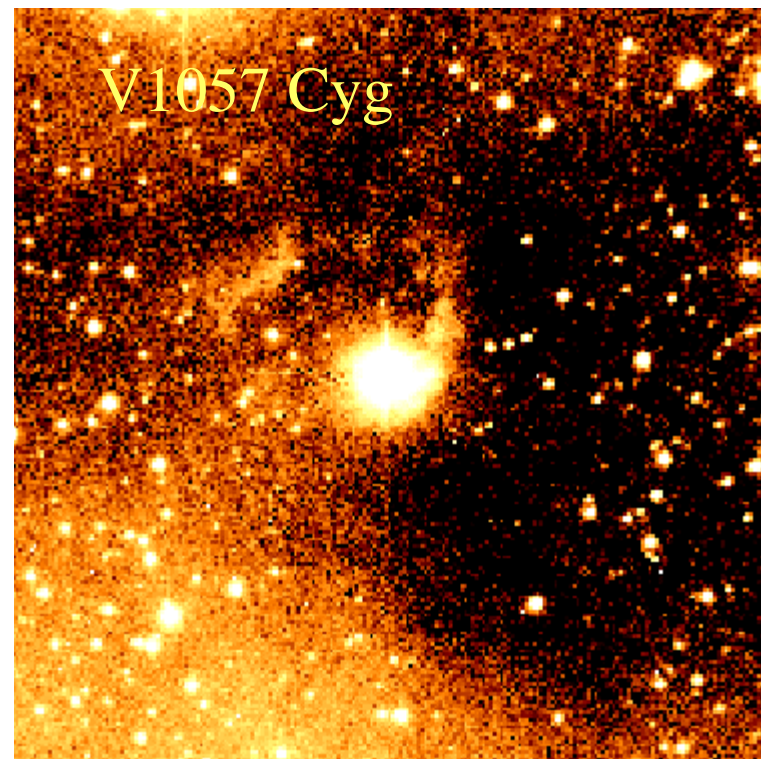
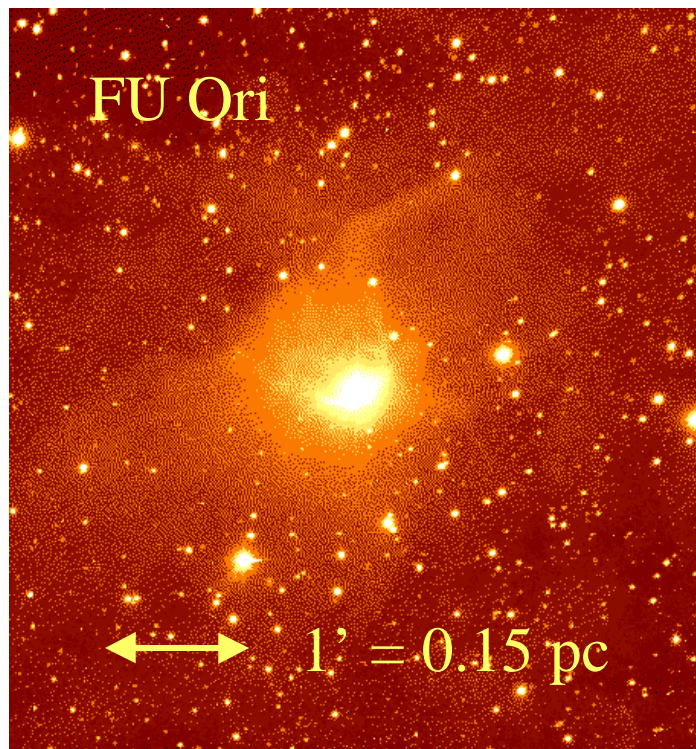


*Calvet
1999*

FU Ori objects and rapid accretion

- Emission from external medium vs. infalling envelope (or outer disk)?

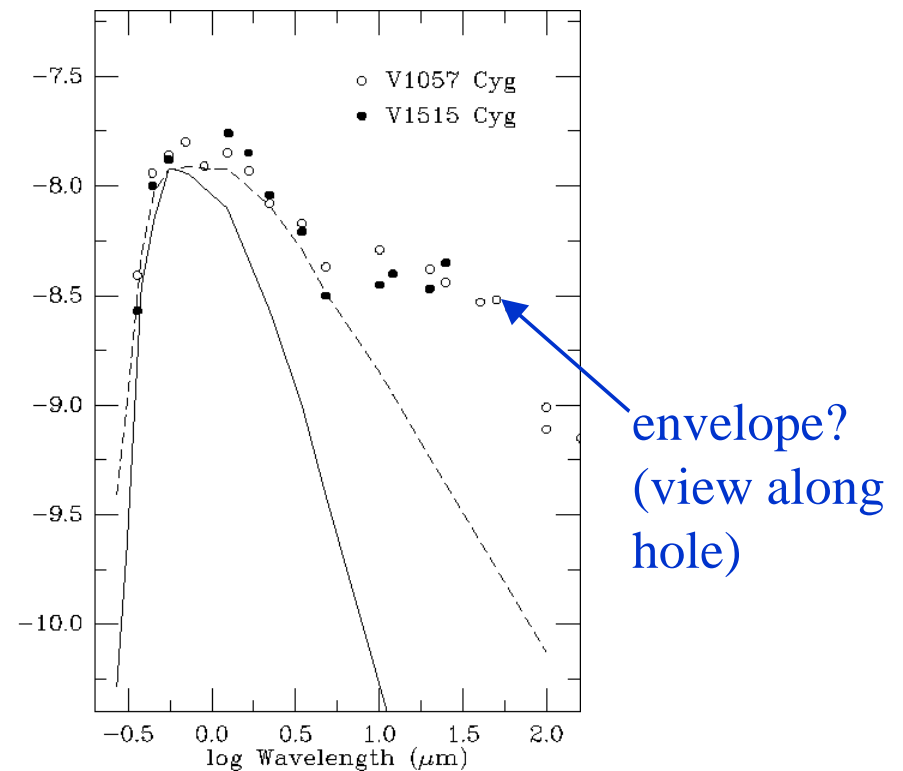
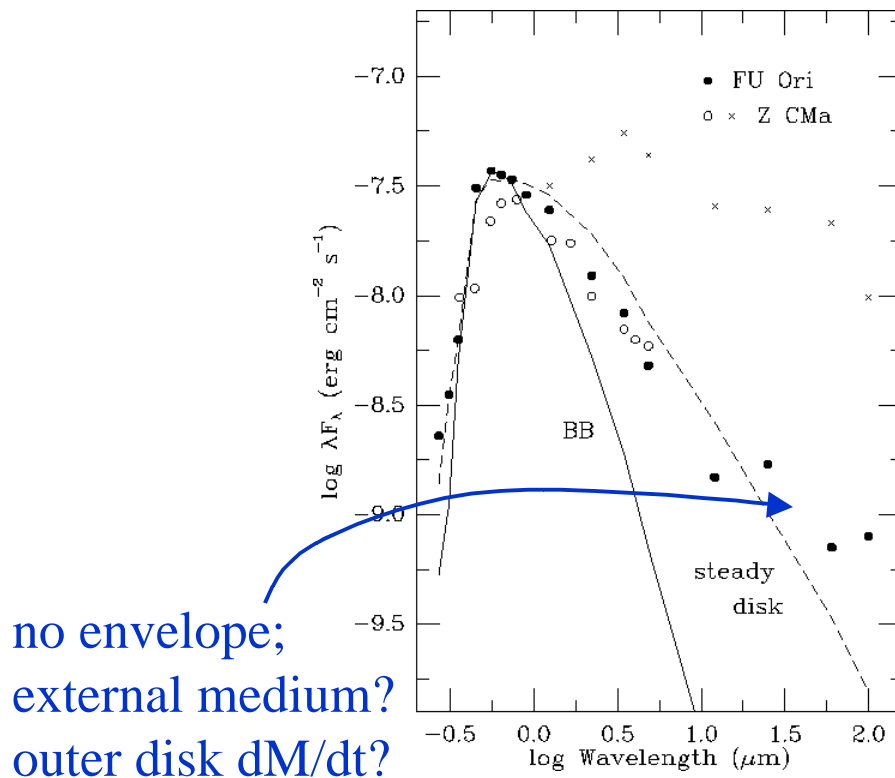
⇒ FIR spatial resolution with SOFIA



FU Ori objects and rapid accretion

- external medium or infalling envelope/disk?

⇒ For luminous ($\sim 500 L_{\odot}$) objects, $T \sim 30\text{K}$ envelope can extend out to $\sim 3000 \text{ AU} \sim 6''$ radius at 500 pc



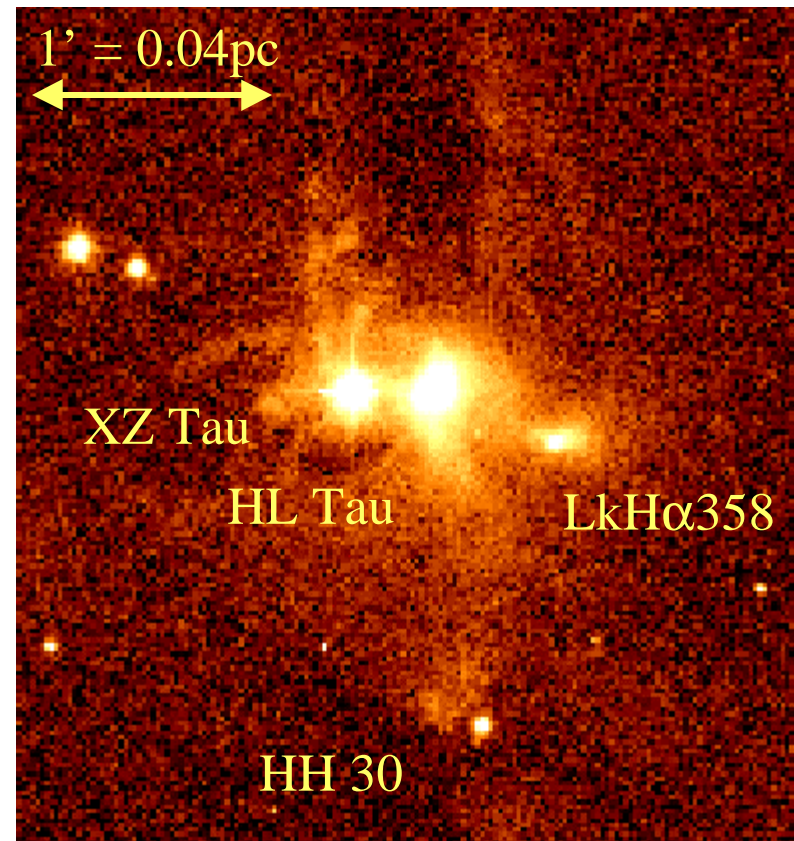
SEDs, accretion, and L_*

- Determination of source luminosities difficult from NIR fluxes and images - scattered light problem for $\lambda \leq 3\mu\text{m}$, disk/inner envelope emission for $\lambda \geq 3\mu\text{m}$
- Scattering particular problem in complicated disk/envelope geometries
- MIR/FIR imaging can help

SEDs, accretion, and L_*

- Scattering particular problem in complicated disk/envelope geometries and environments
- MIR/FIR imaging can help

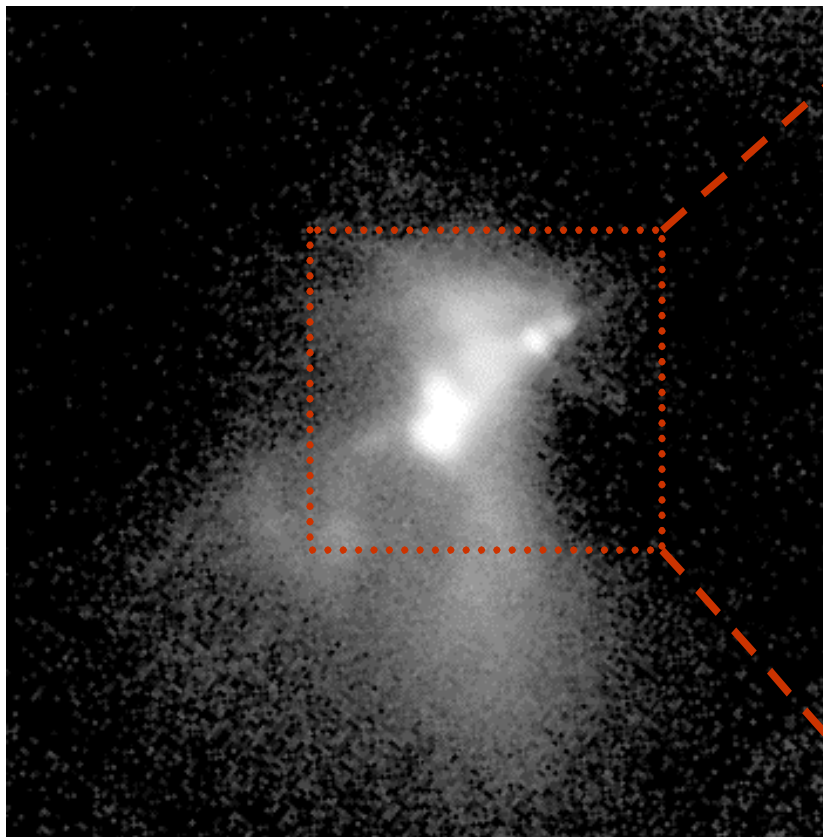
even in “isolated”
star-forming regions,
can be source confusion
in studying envelopes
(e.g., *Welch, Hartmann,
Helfer & Briceno 1999*)



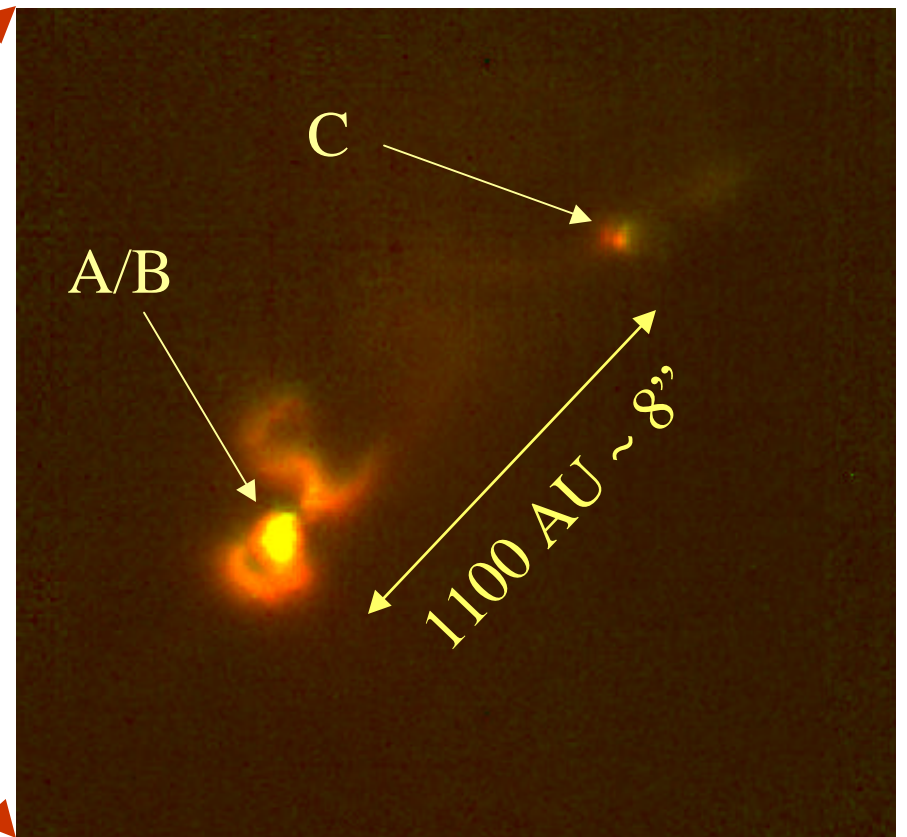
Protostellar source 4325+2402

(Hartmann, Calvet, Allen, Chen, Jayawardhana 1999)

- A/B extended; C is stellar source



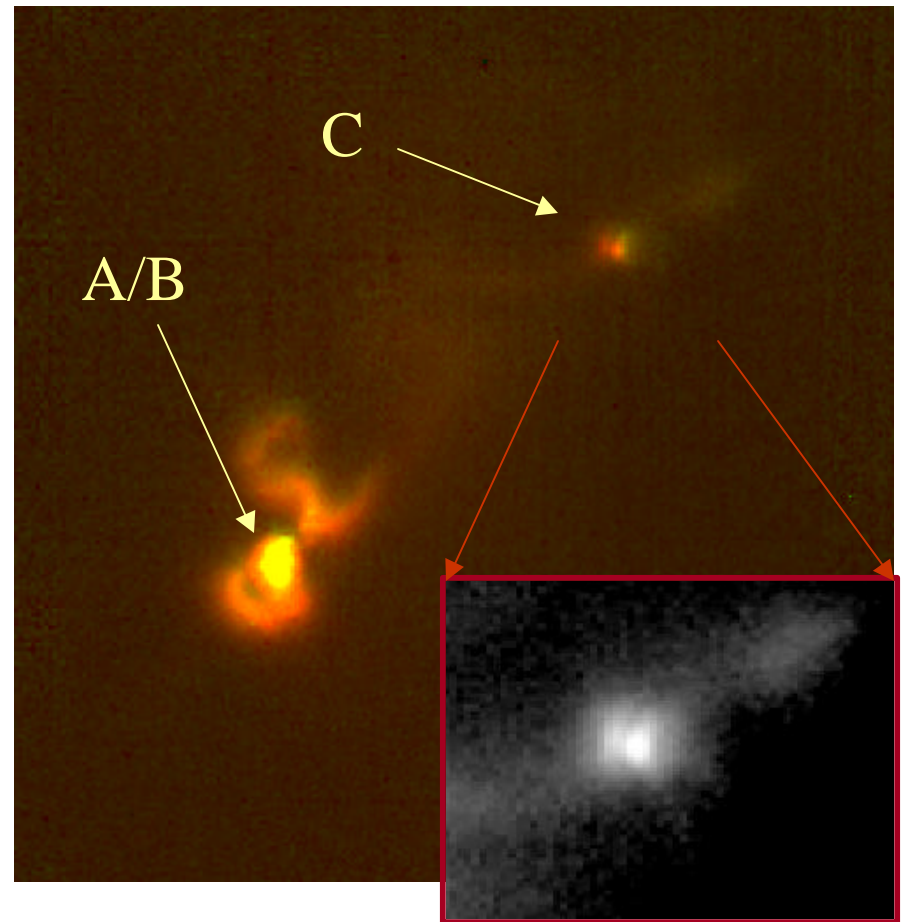
IRTF



NICMOS

Protostellar source 4325+2402

- A/B double? or dust lane?
 - Circumbinary dust ring?
- C is edge-on disk + infall nebula
- arcs related to outflows



Problems of protostellar accretion

- **When is the protostellar mass accreted?**
 - Class 0 phase? Class I phase??
 - FU Ori objects (0, I)? Or other outbursts?
 - embedded objects \Rightarrow (FIR) luminosities?
- SOFIA: spatially-resolved MIR-FIR images:
 - (FIR) luminosities in crowded regions, binaries, differentiate envelope vs. environment
 - emission lines \Rightarrow protostellar accretion tests?

FU Ori objects and rapid accretion

- **Thermal instability? (Bell & Lin 94, 95)**

inner disk is stable only if $dM/dt > 10^{-5} M_{\odot}/\text{yr}$ or
 $dM/dt \leq 10^{-7} M_{\odot}/\text{yr}$

if outer disk accretion rate is $\sim 10^{-6} - 10^{-5} M_{\odot}/\text{yr}$,
inner disk must cycle between high and low states

⇒ Infall to disk at this rate will force instability

FIR imaging:

- dense infalling envelope or extended ISM emission?
- if no envelope; is there a high dM/dt in outer disk?