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 Oris 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?

\[ L(\text{acc}) \approx \left( GM_*/R_* \right) dM/dt ; \]

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

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

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

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

but \( <L>(\text{total, observed}) \, (\text{Class I}) \approx 0.5 \, L_\odot ! \)
The accretion (luminosity) problem

Taurus: \( \frac{dM}{dt} \) (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: $R_* >> R(\text{birthline})$?
  – Reduces $L(\text{acc}) \sim GM_* \frac{dM/dt}{R_*}$
  \[ \Rightarrow L_* \propto \frac{R_*^2}{T^4} \]
  becomes too large unless $T$ very low
  \[ \Rightarrow t_{\text{KH}} \text{ becomes very short - core lifetime too short?} \]

• Magnetospheric infall line profiles for (some) Class I sources can ultimately constrain $M_*/R_*$
  (Muzerolle et al. 1998): emission lines ($\text{Br } \gamma$)
  \[ \Delta v \approx \left(2GM_*/R_*\right)^{1/2} \]

Are there longer-\(\lambda\) lines for higher-$A_V$ sources?
Magnetospheric infall line profiles
(Muzerolle et al. 1998): line width $\approx (2GM_*/R_*)^{1/2}$
$L(\text{Br} \gamma) \propto L(\text{acc})$ (Muzerolle et al. 1998); can use to estimate accretion in Class I sources longer $\lambda$ lines for higher $A_V$ sources?

Taurus optical PMS

Class I sources
• Solution 2: accretion during Class 0 phase?

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

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

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

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: \( \frac{dM}{dt(\text{infall})} \) may be much higher than for Class I sources, \( \frac{dM}{dt} \sim 10^{-4} \, M_\odot/\text{yr} \) 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 \( (\frac{dM}{dt} \approx 10^{-4} M_\odot/yr \text{ for } \sim 100 \text{ yr}) \)
  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\( \mu m \) absorption
Protostellar accretion in bursts?

• Need statistics!

  Taurus: expect only ~ 1 FU; L1551 IRS5?
  (low-L; dM/dt ~ $4 \times 10^{-6} M_\odot/yr$; Rodriguez et al 1999)

⇒ More distant, larger samples

• SEDs, luminosities in highly-extincted, crowded regions

  Many regions have several independent objects within ~ 3000 AU ~ 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 ⇒ SOFIA MIR & FIR imaging

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

\[ \text{Infall rate} = 4 \times 10^{-6} \, \text{M}_\odot \, \text{yr}^{-1} \]

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 (~500 L☉) objects, T~30K envelope can extend out to ~ 3000 AU ~ 6” radius at 500 pc

no envelope; external medium? outer disk dM/dt?

envelope? (view along hole)
**SEDs, accretion, and L***

- Determination of source luminosities difficult from NIR fluxes and images - scattered light problem for $\lambda \leq 3\mu m$, disk/inner envelope emission for $\lambda \geq 3\mu m$
- 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

![Image of protostellar source 4325+2402 with annotations for A/B and C.]
Protostellar source 4325+2402

- A/B double? or dust lane?
  - Circumbinary dust ring?
- C is edge-on disk + infall nebula
- arcs related to outflows
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FU Ori objects and rapid accretion

• Thermal instability? (Bell & Lin 94, 95)
  
  inner disk is stable only if \( \frac{dM}{dt} > 10^{-5} \, M_\odot/yr \) or 
  \( \frac{dM}{dt} \leq 10^{-7} \, M_\odot/yr \)

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

  \( \Rightarrow \) 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 \( \frac{dM}{dt} \) in outer disk?