The Early Evolution of low mass stars and Brown Dwarfs

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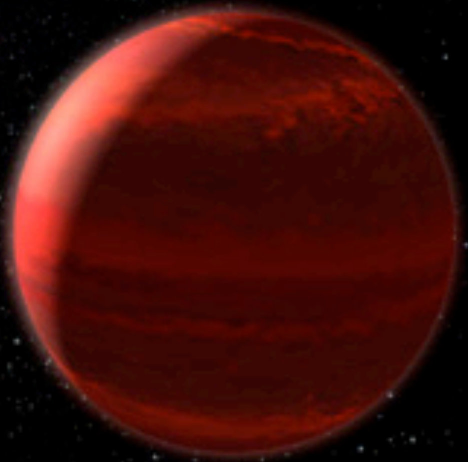


1. Some observational/theoretical facts

- Spread in the HRD
- Lithium depletion
- Evidence for episodic accretion
  - Embedded protostars
  - FU Orionis objects
  - Models of disk instability

2. Effects of accretion on VLM/BD

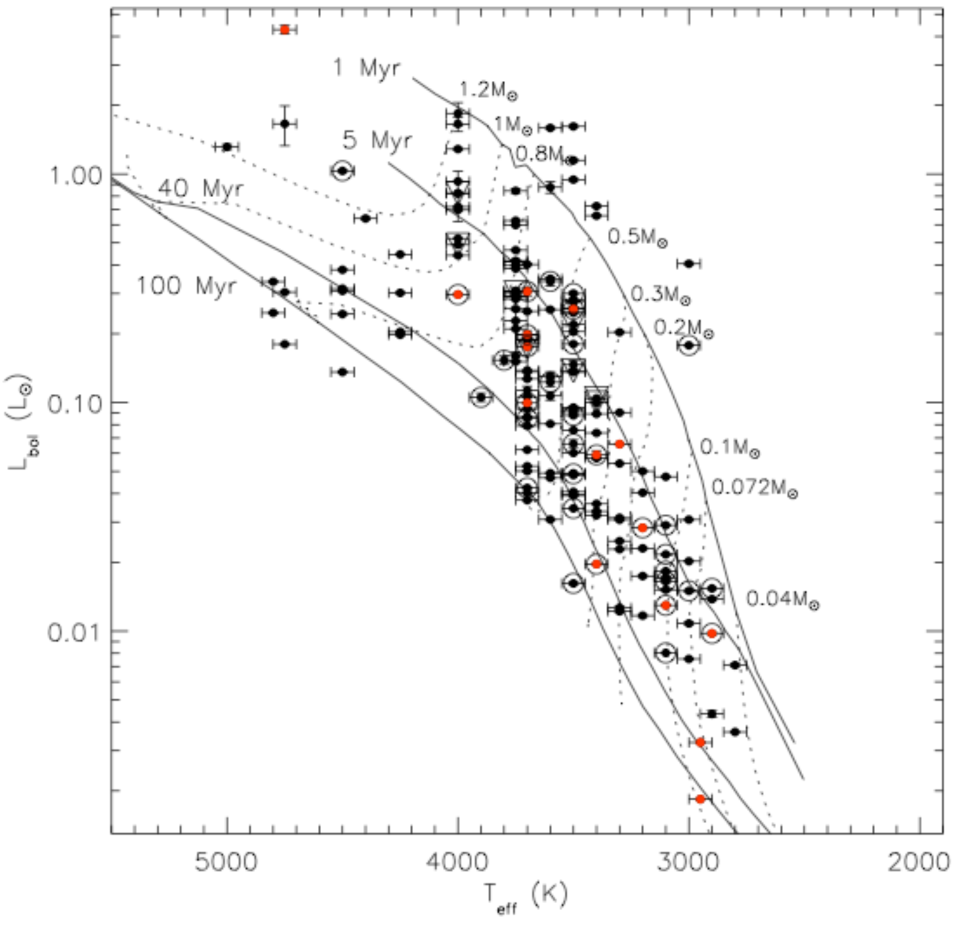
3. Toward a consistent (unified?) picture

1. Some observational/theoretical facts

- **Spread in the HRD**

Well known problem: spread in Teff-L diagram of young cluster members (1-10 Myr)

Age spread?



Bayo et al. 2011 λ Orionis (~5Myr)

- **Lithium depletion**

- Large lithium scatter and anomalous Li depletion in young cluster members of a few Myr old

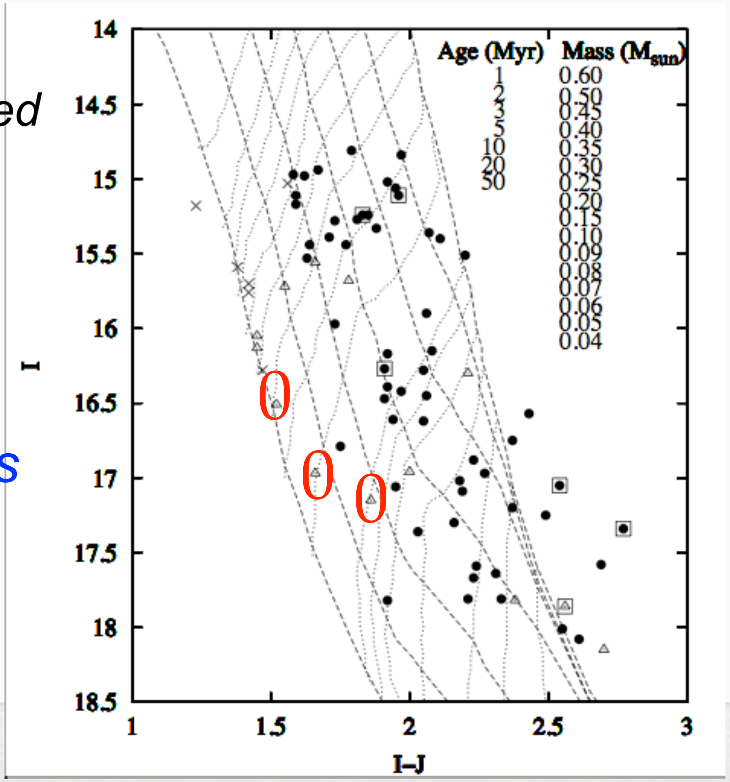
(Kenyon et al. 2005; Sacco et al. 2007, 2008; Prizinsano et al. 2007)

σ ori cluster ~ 5 Myr

(Kenyon et al. 2005)

- lithium *(expected at this age)*

Δ no lithium



Abundances of lithium in a few low mass members suggest an older age for these objects (> 10 Myr).

☛ HRD spread and lithium scatter:

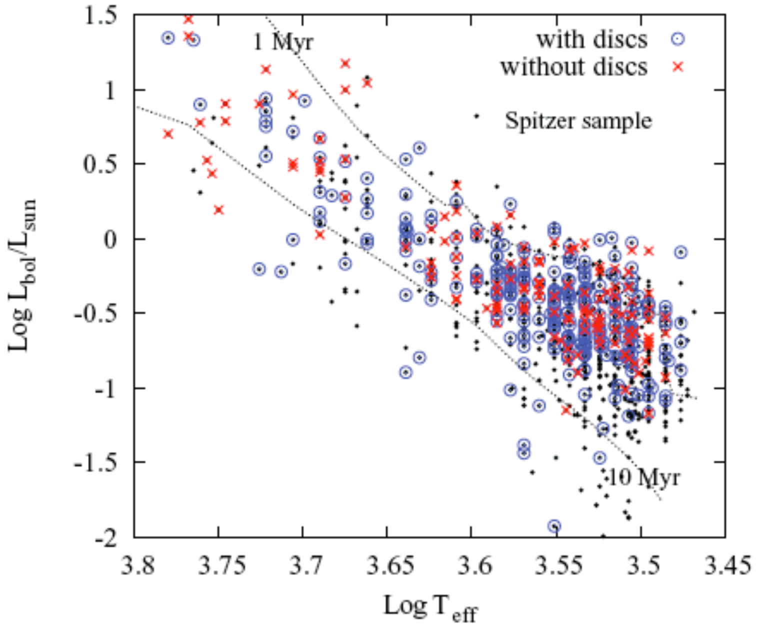
Used as argument in favor of an **age spread** (Palla et al. 2005)

Idea of slow star formation (quasi-static contraction of protostellar cores)

☛ Idea strongly debated and **against** our current understanding of star formation *(dynamical picture with supersonic turbulence)*

(Hartmann 2001; Ballesteros-Paredes & Hartmann 2007; Hennebelle & Chabrier 2009,2010)

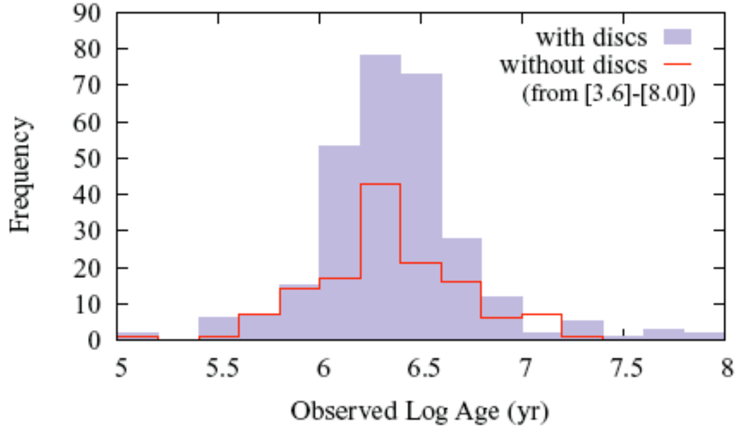
☛ Observations of stars with and without discs in the Orion Nebula Cluster (*Jeffries* et al. 2011)



No significant difference in the mean ages/age distribution of stars with and without discs

→ consistent with coeval population

No age spread



➙HRD spread : Accretion effects at early stages of evolution?
(Baraffe et al. 2009; Baraffe & Chabrier 2010; Hosokawa et al. 2011)

- Evidence for episodic accretion
  - Recent observations of embedded protostars in clouds *(Enoch et al. 2009; Evans et al. 2009; Dunham et al. 2010)*

---> large population of low luminosity class I sources
---> small fraction of very luminous sources

⇒ Suggest long quiescent phases of accretion ($M_{dot} \leq 10^{-6}$ $M_{\odot}yr^{-1}$) interrupted by episods of high accretion ($M_{dot} \geq 10^{-5}$ $M_{\odot}yr^{-1}$) of short duration

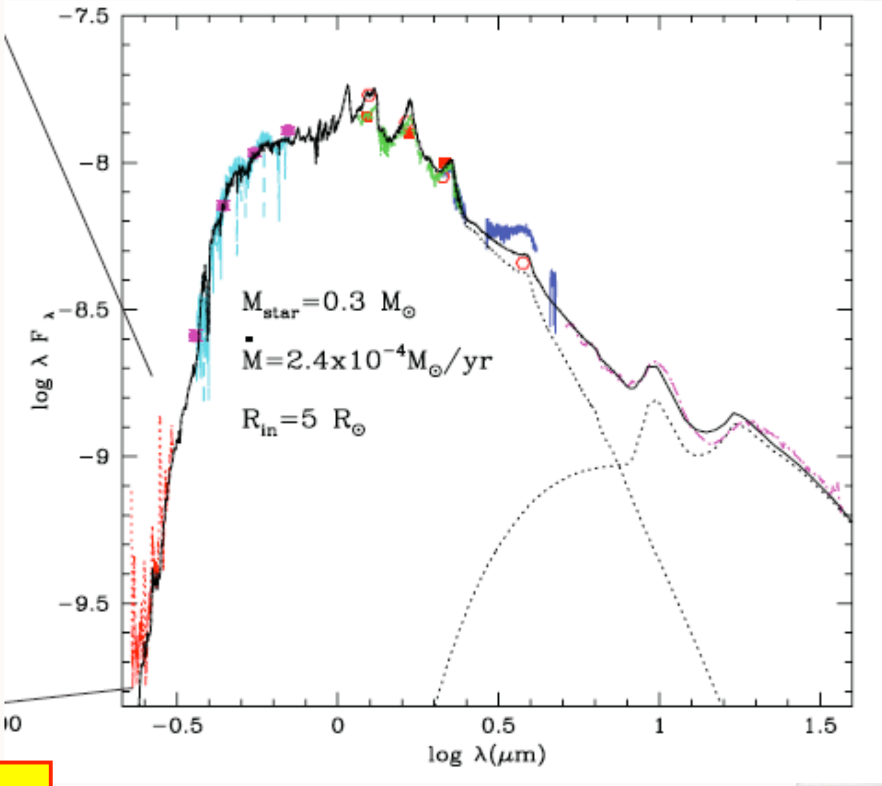
- Other observational evidences for episodic accretion:

- FU Orionis objects provide evidences for the existence of short episodes of rapid accretion ($M_{dot} > 10^{-4}\ M_{\odot} yr^{-1}$) *(Hartmann & Kenyon 1990)*

- FU Ori objects provide excellent laboratories to test effects of strong accretion bursts on the structure of the central object *(Hartmann et al. 2011)*

Hartmann et al. 2011:

Match of observed SED of FU Ori
based on steady disk model
(Zhu et al. 2007; 2008)



☛ **Central object ~ 0.3 $M_\odot$**
Inner disk radius ~ 5 $R_\odot$

☛ **absence of magnetospheric accretion and of hot boundary layer emission**

⇒ No BLD: accreted material does not radiate significant fraction of its kinetic energy

⇒ Significant heating of the protostellar upper layers

⇒ **expansion of the star ($R \sim R_{in}$)**

(i.e «hot» accretion)

- # Theoretical models for episodic accretion

Disk instabilities produce outbursts of accretion onto the protostar:

- **Gravitational instabilities** *(Vorobyov & Basu 2005, 2006, 2010)*
- Combination of **gravitational and magnetorotational instabilities** *(Zhu, Hartmann, Gammie 2008)*

Systematic study of *Vorobyov & Basu 2010; Vorobyov 2010*

☛ Variation of the prestellar core masses (starless cloud core M_c):
$M_c = 0.16\ M_\odot - 1.7\ M_\odot$
☛ Variation of rotational to gravitational energy ratio: $\beta = 10^{-4} - 7\ 10^{-2}$

⇒ Higher **initial core mass** M_c and higher **initial rate of rotation** β favors more fragmentation

⇒ Intensity of the burst mode correlates with the disk's propensity to fragment

☛ **burst intensity (and maximum Mdot) increases with Mc <u>and</u> β**

High Mc ($\gtrsim 1\ M_\odot$) <u>and</u> high β ($\gtrsim 10^{-2}$) can produce bursts $\gtrsim 10^{-4}\ M_\odot$/yr (i.e Fu Ori type bursts)

2. Effect of accretion on VLM/BD evolution

Idea that accretion at early stages of evolution can produce the observed HRD spread
⇒ **No need to invoke an age spread** *(Baraffe et al. 2009; Baraffe & Chabrier 2010)*

Recently questioned by Hosokawa et al. 2011 (at least for objects with $T_{eff} < 3500K$)

Baraffe et al. results

(i) Assume **non spherical accretion** (affects very small fraction of stellar surface)

(ii) Accreted matter brings internal energy: $\varepsilon G M M_{dot}/R$

(accretion from a thin disk: $\varepsilon \leq 0.5$)

Fraction α absorbed by the central object

$$L_* = \underset{\substack{\uparrow \\ \text{radiated away}}}{(1-\alpha)\epsilon \frac{GM_*\dot{M}}{R_*}} + \underset{\substack{\uparrow \\ \text{absorbed}}}{\alpha\epsilon \frac{GM_*\dot{M}}{R_*}} + \underset{\substack{\uparrow \\ \text{intrinsic}}}{\int_M \epsilon_{\rm nuc}\, dm} - \underset{\substack{\uparrow \\ \text{mass increase}}}{\int_M T\left\{ \left(\frac{\partial S}{\partial t}\right)_q - \dot{m}\left(\frac{\partial S}{\partial m}\right)_t \right\} dm}$$

(iii) Adopt simplified accretion rates inspired by burst mode of accretion of

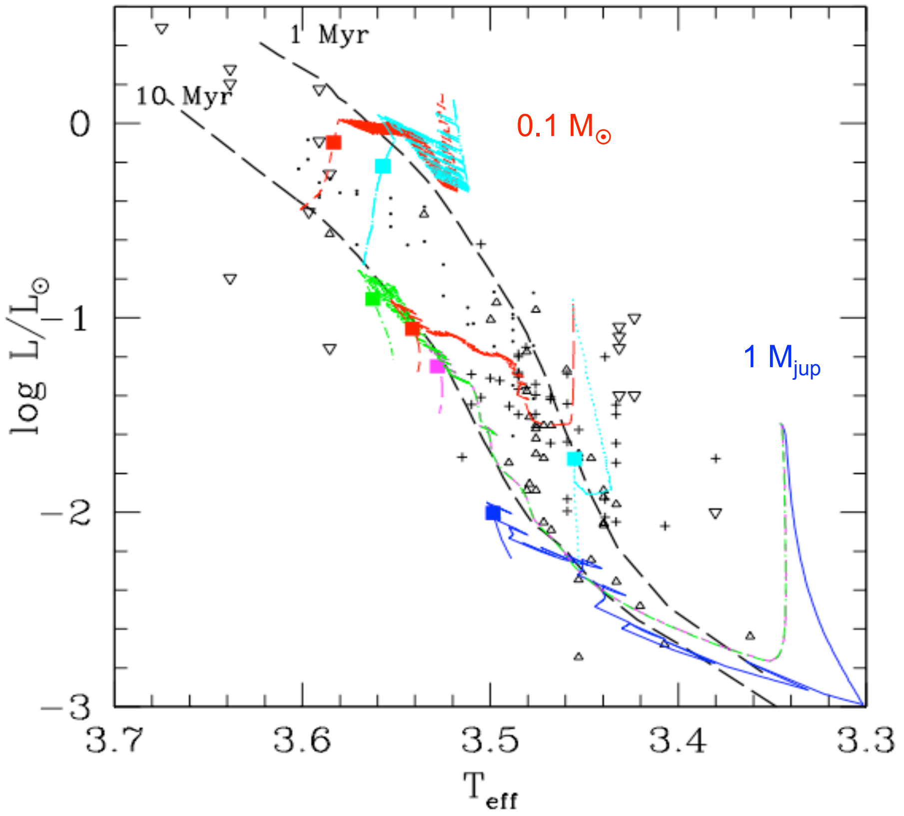
Vorobyov & Basu (2005, 2006)

$N_{burst} = 10\text{-}100$; $\Delta t_{burst} = 100$ yr; $\Delta t_{quiet} = 10^3 - 10^4$ yr $M_{dot} = 10^{-4} - 5\ 10^{-4}\ M_\odot/\mathrm{yr}$

⇒ Can produce a spread in the HRD at ages of ~ few Myr assuming

(i) **cold accretion α=0**
(ii) **Initial mass M_i = 1 M_{Jup} - 0.1 $M_\odot$**
(iii) **No need for hot accretion**

Baraffe et al. 2009



■ position at 1 Myr

⇒ Can explain Li scatter and unexpected Li depleted objects *(More compact and hotter structure ⇒ hotter T_c ⇒ faster Li depletion*

(Baraffe & Chabrier 2010)

M_i ⇔ mass of seed protostar ⇔ mass of second Larson core

☹ **Requires high initial masses M_i**

M_i ⇔ mass of seed protostar ⇔ mass of second Larson core

- Minimum mass for opacity-limited fragmentation: 3 M_{Jup}
  (Boyd & Whitworth 2006)
- Minimum mass for Primary Fragmentation : 1-4 M_{Jup}
  (Whitworth & Stamatellos 2006)
- RHD simulations of first and second collapse: ~ 10 M_{Jup}
  (Masunaga et al. 1998; 2000)

⇒ Most reasonnable assumption: $M_i \sim 1 - 10\ M_{Jup}$

☹ **Assume cold accretion**

In contradiction to findings of Hartmann et al. 2011 for Fu Ori
accretion should induce expansion (by factor ~ 2 in radius for Fu Ori burst) and not contraction

- **Hosokawa et al. results**

(i) Assume **“cold” accretion** *(similar to Baraffe et al.)*

(ii) and **“hot” accretion** *(different from Baraffe et al.)*

Spherical accretion (similar to accretion shock jump conditions of Stahler et al. 1980)

⇒ substantial amount of energy absorbed by protostar

⇔ corresponding to upper limit case **α=1** in Baraffe et al.

(iii) Adopt various accretion rates: **constant, burst like, simulations** of Offner et al. (2009).

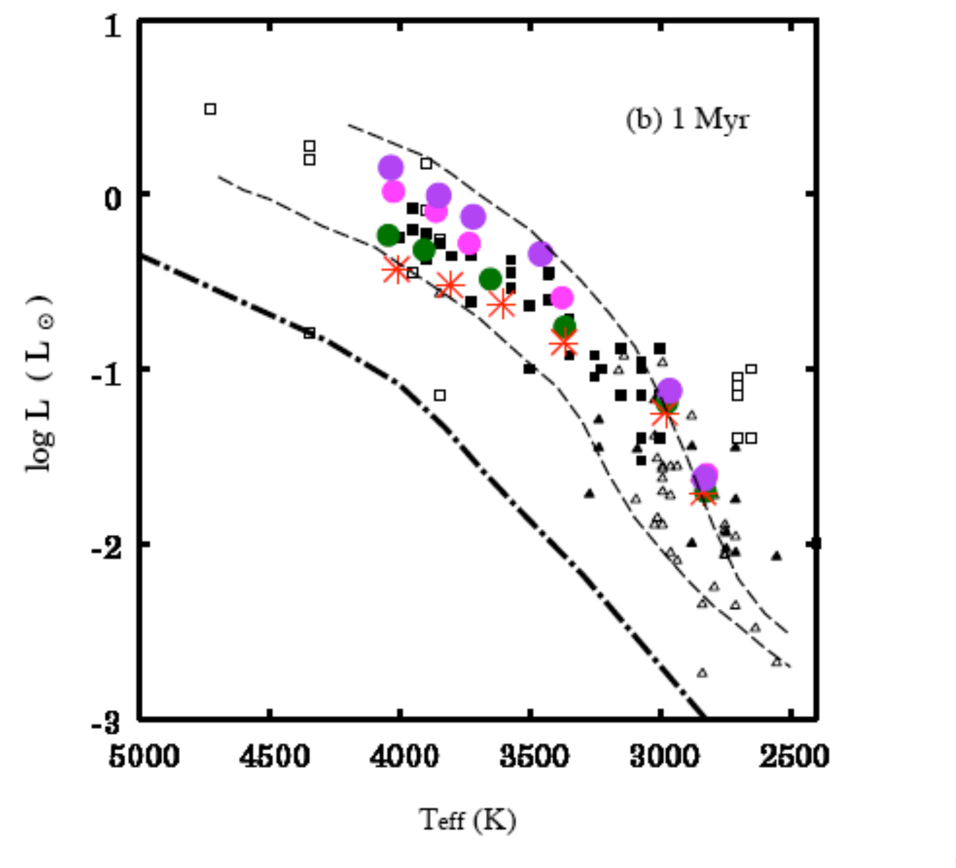
⇒ Find similar effects of accretion on the structure of VLM/BD as Baraffe et al.

(More compact structure; object looks older; Hot accretion compensates effect of mass accretion)

⇒ Can produce a spread in the HRD at ages of ~ few Myr assuming

(i) **cold/hot accretion**
(ii) **Initial mass M_i = 0.01 $M_\odot$**
(Masunaga & Inustuka 2000)

But only for Teff ≳ 3500K

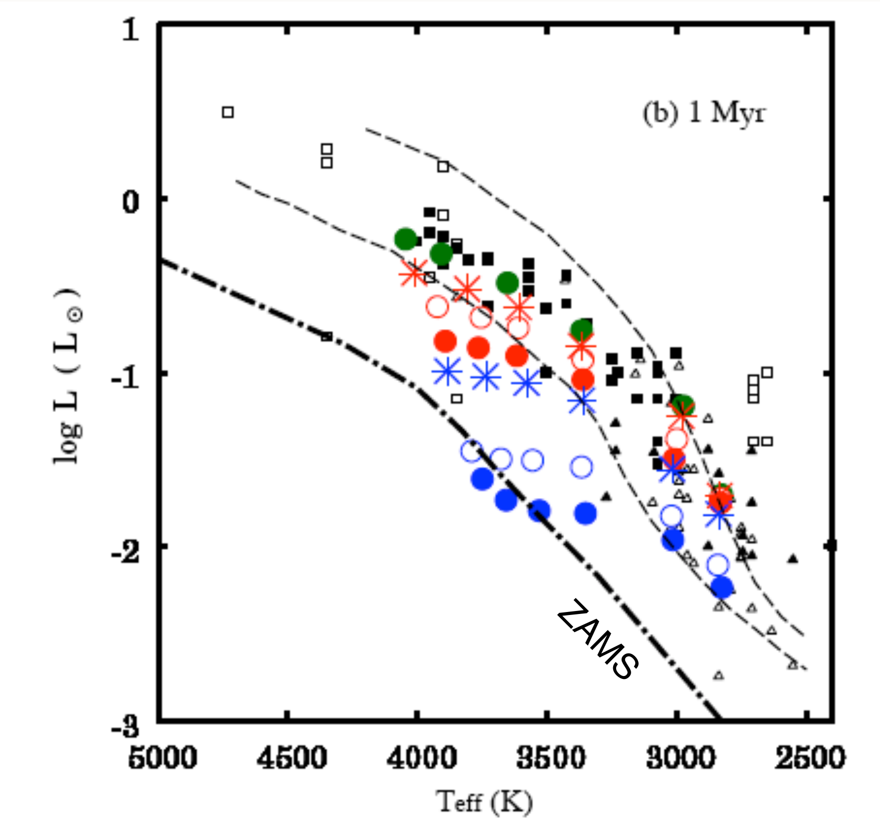


☛ For low mass objects with **T_{eff} < 3500K**, spread obtained **only** if seed protostar of 0.01 $M_\odot$ has **extremely small radius** (~ 0.2-0.3 $R_\odot$)

(Masunaga & Inutsuka 2000 → initial radius 4 $R_\odot$)

Hosokawa et al. 2011

Such initial seeds would yield an overproduction of objects with T_{eff} > 3500K below 10 Myr isochrones



Blue symbols: $R_i \leq 0.3\ R_\odot$

⇒ Conclusion of Hosokawa et al: accretion cannot produce a spread for the coolest stars ⇒ ages are reliable for $T_{eff} \lesssim$ 3500K

☹ **Fixed initial mass M_i= 0.01 $M_\odot$**

Variation of M_i from 1 - 10 M_{Jup} can produce a spread for the lowest mass

⇒ This would change the conclusion of the Hosokawa et al. work

3.Toward a consistent (unified?) picture

Baraffe, Vorobyov, Chabrier 2011

- Accretion rates predicted by simulations of burst mode of accretion of Vorobyov & Basu with a distribution on pre-stellar cores ($M_c = 0.085 - 1.5\ M_\odot$)

  → produce stars/BD of various masses from ~ $0.065 - 1\ M_\odot$
  → Variation of initial rotational velocity

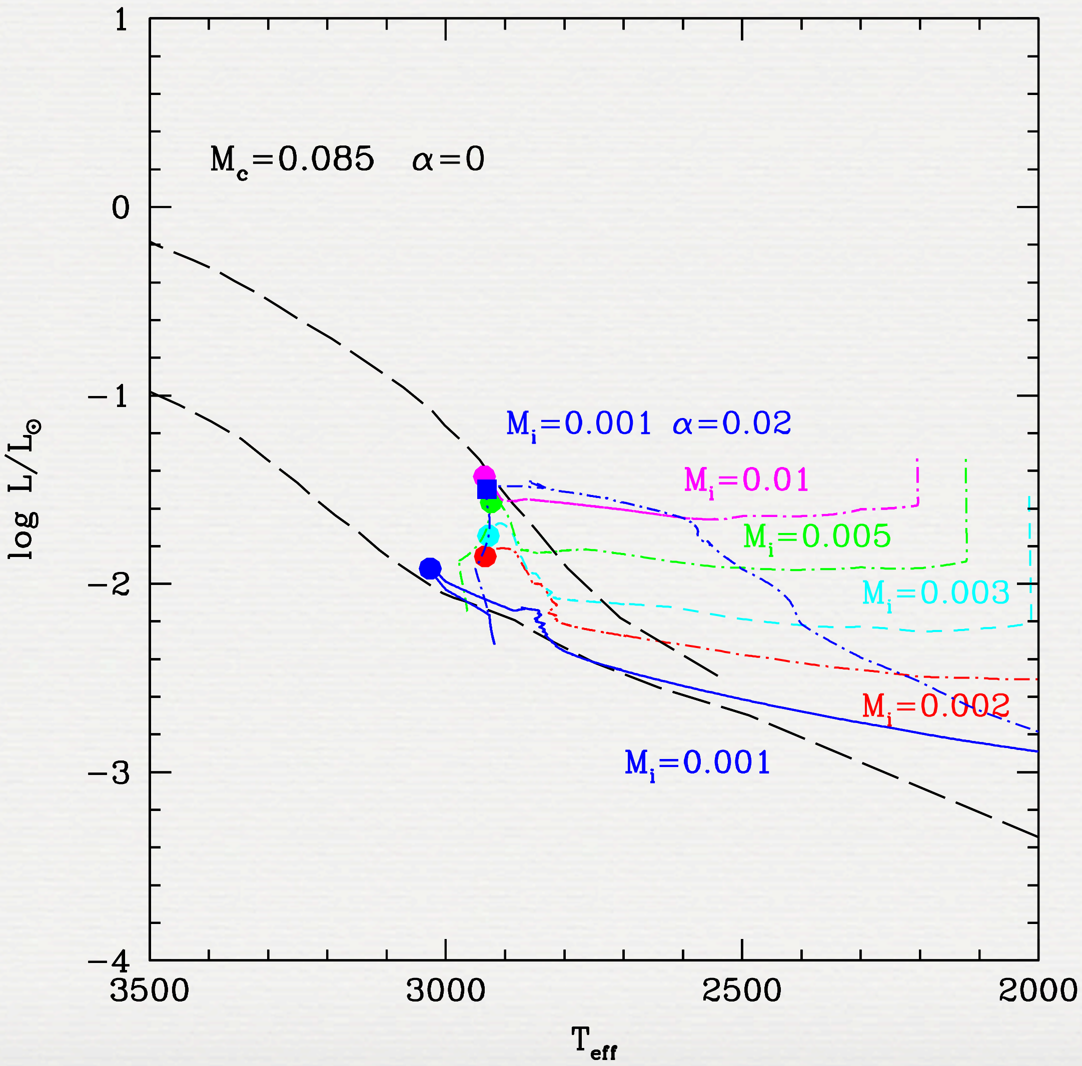
- Range of initial protostar seed masses (2nd core mass): 1-10 M_{Jup}

- Moderate absorption of accretion energy: $\alpha = 0 - 0.20$

Lowest part of the HRD (T_{eff} < 3500K, small initial M_c)

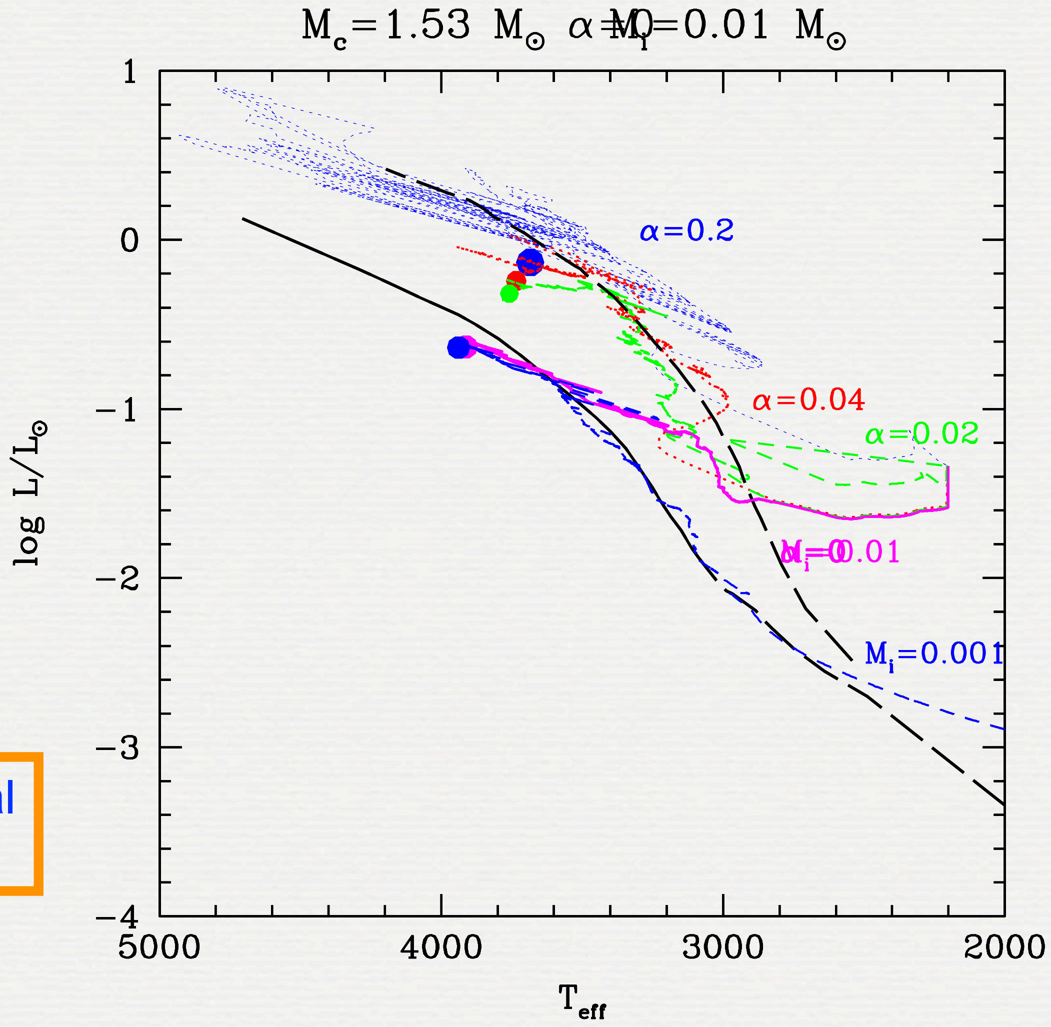
produce a spread with

- M_i = 1 - 10 M_{Jup}
- very moderate α (α= 0 to a few %)



Highest (brightest) part of the HRD (T_{eff} > 3500K, larger initial M_c)

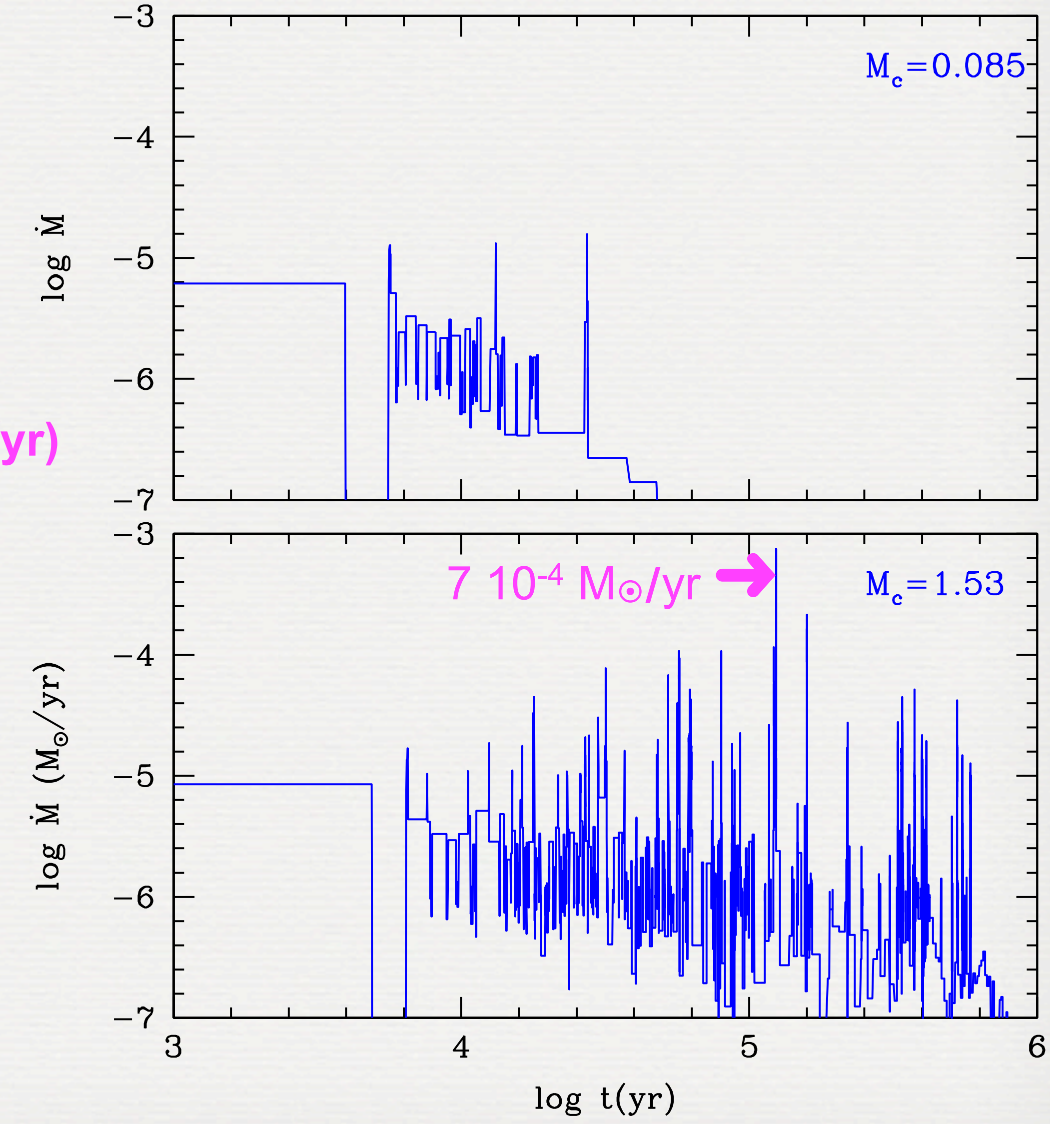
produce a spread with
- M_i = 1 - 10 M_{Jup}
- small to moderate α (α= 0 to a 20 %)



Similar effects with varying initial masses

Relation between α (fraction of energy absorpbed by proto-object) and burst intensity?

- M_c increases ⇒ burst intensity increases



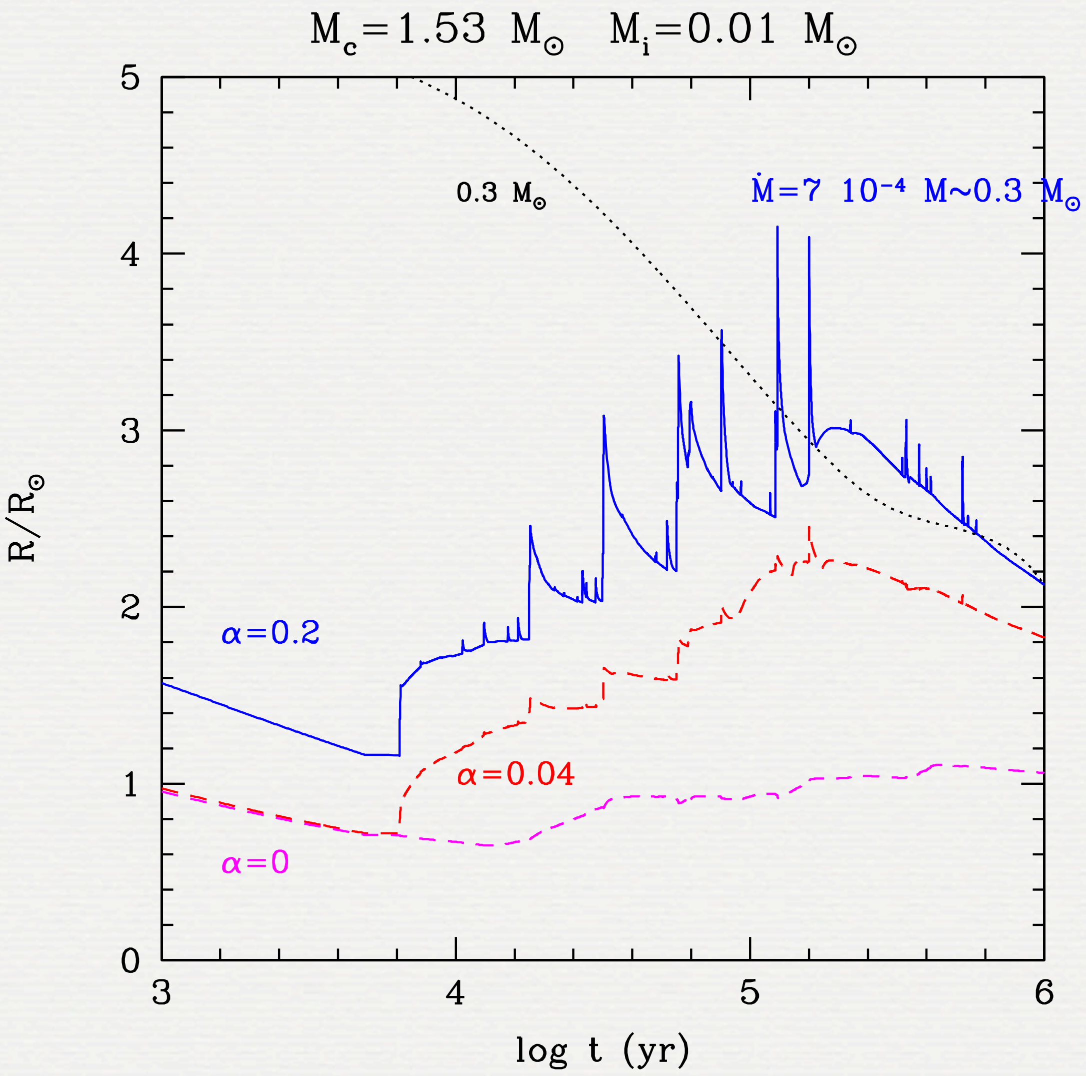
- Large M_c **and** large initial angular momentum can produce intense Fu Ori-like bursts (> 10^{-4} M⊙/yr)

- For such high bursts, change of process/geometry of accretion onto protostellar surface?

☛ ***Transition from magnetospheric accretion to thick disk accretion??***

- ☛ Interesting: most intense bursts with **α ~20%**

  ⇒R★ can increase by a factor of 2



CONCLUSION

Idea that early accretion history can produce the observed HR spread is still more than alive.....

It is compelling that a scenario based on:

- Variation of pre-stellar core masses with varying initial angular momentum
  ☛ variation of bursts intensity/properties

- Variation of protostar seed masses (2nd core mass) from 1 - 10 M_{Jup}

- Moderate absorption of accretion energy onto proto-object (few % to 20%)
  ☛ linked to bursts intensity (and thus to M_c and E_{rot})

☺ can produce a spread in the HRD (+ extreme lithium depletion)
☺ can explain Fu Ori observations (large radius of central object)
☺ can explain observations of embedded objects (Evans et al. ; Dunham et al.)

PERSPECTIVES

- **Simulations of 2nd core: mass and radius (initial entropy)?**
  properties of accretion shock (first core accretion shock found to be supercritical, i.e all acretion shock energy radiated away Commercon et al. 2011)

- **Burst mode of accretion models: effect of M_c and initial angular momentum?**

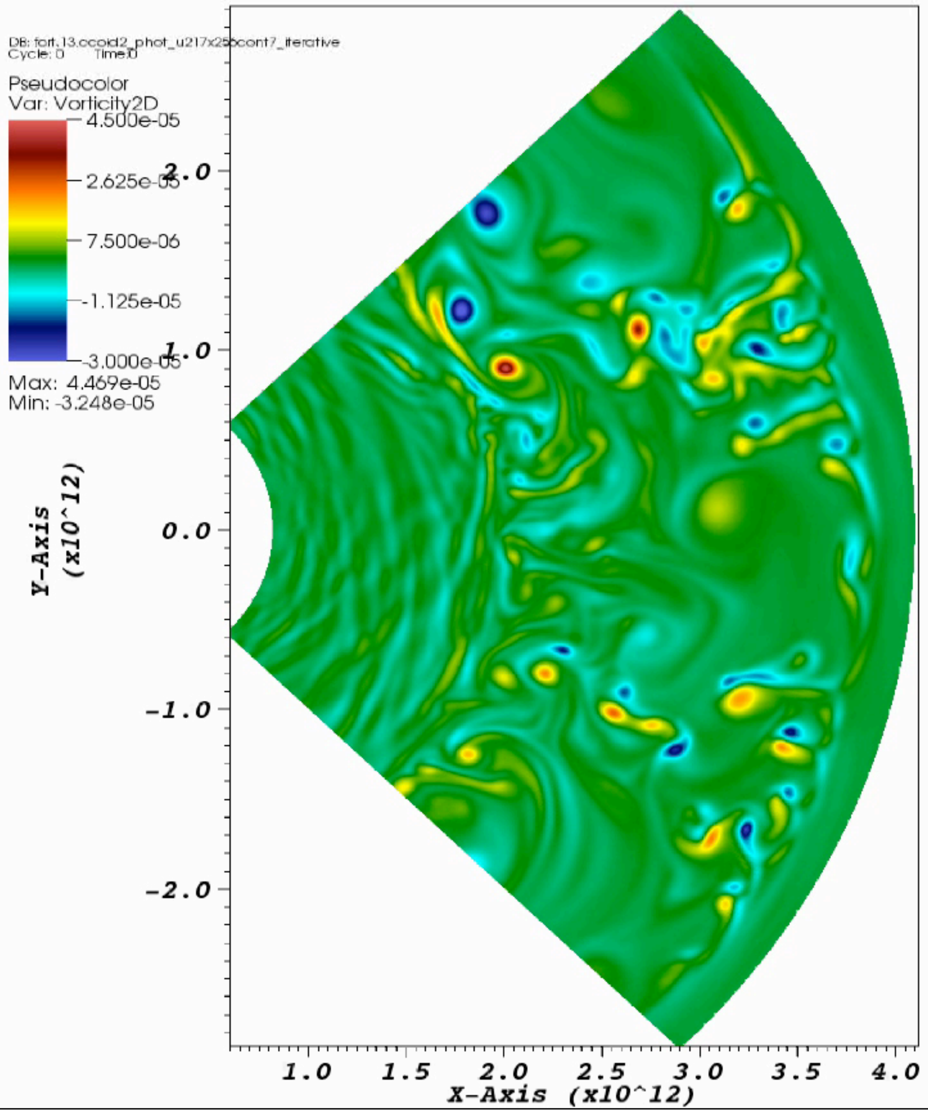
- **Star - disk interaction:**
  Is there a threshold in Mdot ➙ transition from “cold” to “hot” accretion
  (transition from magnetospheric to thick disk accretion?)

- **Effect of accretion on the structure of proto-VLM/BD:**
  How well to do we treat accretion in 1D stellar evolution?

Development of a multi-D time implicit code

(Viallet, Baraffe, Walder 2011)

- **Timestep not limited: can follow evolution on thermal timescale**
- **Yet: describe 80% of a star in radius (50% convective envelope)**



M_{dot}, α

Redistribution of matter/heat?
Formation/lifetime of radiative zones?

$CFL_{hydro} \sim 100$