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?**
• 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

Evidence for episodic accretion

- Recent observations of embedded protostars in clouds
  \((\text{Enoch et al. 2009; Evans et al. 2009; Dunham et al. 2010})\)

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

\[ \Rightarrow \text{Suggest long quiescent phases of accretion } (M_{\text{dot}} \leq 10^{-6} \text{ } M_{\odot}\text{yr}^{-1}) \]
interrupted by \text{episods of high accretion } (M_{\text{dot}} \geq 10^{-5} \text{ } M_{\odot}\text{yr}^{-1}) \text{ of short duration}
- Other observational evidences for episodic accretion:

  - FU Orionis objects provide evidences for the existence of short episodes of rapid accretion ($M_{\text{dot}} > 10^{-4} M_{\odot} \text{yr}^{-1}$)  
    
    (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☉
  - Inner disk radius ~ 5 R☉

- 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 ~ 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 $M_c$):
  \[ M_c = 0.16 \, M_\odot \text{ - } 1.7 \, M_\odot \]

- Variation of rotational to gravitational energy ratio: $\beta = 10^{-4} - 7 \times 10^{-2}$

⇒ Higher **initial core mass** $M_c$ and higher **initial rate of rotation** $\beta$ favors more fragmentation

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

⇒ **burst intensity (and maximum Mdot)** increases with $M_c$ and $\beta$

High $M_c$ ($\gtrsim 1 \, M_\odot$) and high $\beta$ ($\gtrsim 10^{-2}$) 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  \textit{(Baraffe et al. 2009; Baraffe & Chabrier 2010)}

Recently questioned by Hosokawa et al. 2011 (at least for objects with $T_{\text{eff}} < 3500K$)
• **Baraffe et al. results**

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

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

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

**Fraction \( \alpha \) absorbed** by the central object

\[
L_* = (1 - \alpha) \varepsilon \frac{G M_* \dot{M}}{R_*} + \alpha \varepsilon \frac{G M_* \dot{M}}{R_*} + \int_M \epsilon_{nuc} \, dm - \int_M T \left\{ \left( \frac{\partial S}{\partial t} \right)_q - \dot{m} \left( \frac{\partial S}{\partial m} \right)_t \right\} \, dm
\]

- radiated away
- absorbed
- intrinsic
- mass increase

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


\( N_{\text{burst}} = 10 - 100 \); \( \Delta t_{\text{burst}} = 100 \) yr; \( \Delta t_{\text{quiet}} = 10^3 - 10^4 \) yr \( M_{\dot{\text{dot}}} = 10^{-4} - 5 \times 10^{-4} \) M\(_{\odot}\)/yr
Can produce a spread in the HRD at ages of ~ few Myr assuming

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

Can explain Li scatter and unexpected Li depleted objects

*(More compact and hotter structure)*

$\Rightarrow$ hotter $T_c$ $\Rightarrow$ faster Li depletion

*(Baraffe & Chabrier 2010)*

$M_i \leftrightarrow$ mass of seed protostar $\leftrightarrow$ mass of second Larson core
Requires high initial masses $M_i$

$M_i \Leftrightarrow \text{mass of seed protostar} \Leftrightarrow \text{mass of second Larson core}$

- Minimum mass for opacity-limited fragmentation: $3 \, M_{\text{Jup}}$  
  \textit{(Boyd & Whitworth 2006)}

- Minimum mass for Primary Fragmentation: $1-4 \, M_{\text{Jup}}$  
  \textit{(Whitworth & Stamatellos 2006)}

- RHD simulations of first and second collapse: $\sim 10 \, M_{\text{Jup}}$  
  \textit{(Masunaga et al. 1998; 2000)}

$\Rightarrow \text{Most reasonable assumption: } M_i \sim 1 - 10 \, M_{\text{Jup}}$

Assume cold accretion

In contradiction to findings of Hartmann et al. 2011 for Fu Ori
\textit{accretion should induce expansion (by factor $\sim 2$ 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 $\alpha = 1$ 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 & Inostuka 2000)*

But only for $T_{\text{eff}} \gtrsim 3500K$
For low mass objects with $T_{\text{eff}} < 3500K$, 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 $R_\odot$)

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

**Hosokawa et al. 2011**

![Graph showing relation between $T_{\text{eff}}$ and $\log L / L_\odot$ with blue symbols indicating $R_i \leq 0.3 R_\odot$.]
⇒ Conclusion of Hosokawa et al: accretion cannot produce a spread for the coolest stars ⇒ ages are reliable for $T_{\text{eff}} \leq 3500K$

😊 Fixed initial mass $M_i = 0.01 M_\odot$

Variation of $M_i$ from 1 - 10 $M_{\text{Jup}}$ 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 $\sim 0.065 - 1 \, M_\odot$
  
  → Variation of initial rotational velocity

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

- Moderate absorption of accretion energy: $\alpha = 0 - 0.20$
Lowest part of the HRD ($T_{\text{eff}} < 3500\text{K}$, small initial $M_c$)

produce a spread with
- $M_i = 1 - 10 \ M_{\text{Jup}}$
- very moderate $\alpha$ ($\alpha = 0$ to a few %)
Highest (brightest) part of the HRD ($T_{\text{eff}} > 3500K$, larger initial $M_c$)

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

Similar effects with varying initial masses
Relation between $\alpha$ (fraction of energy absorbed by proto-object) and burst intensity?

- $M_c$ increases $\Rightarrow$ burst intensity increases

- Large $M_c$ and large initial angular momentum can produce intense Fu Ori-like bursts ($> 10^{-4} M_\odot/yr$)

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

$\Rightarrow$ Transition from magnetospheric accretion to thick disk accretion??
Interesting: most intense bursts with $\alpha \sim 20\%$

$\Rightarrow R_\star$ 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 accretion 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 $\rightarrow$ 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
(\textit{Viallet, Baraffe, Walder 2011})

\begin{itemize}
  \item Timestep not limited: can follow evolution on thermal timescale
  \item Yet: describe 80\% of a star in radius (50\% convective envelope)
\end{itemize}

\textbf{CFL_{hydro} \sim 100}

\textbf{M_{dot}, \alpha}

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