Brown dwarf & star formation and the bottom of the IMF: a critical look

Gilles Chabrier
ENS-Lyon
U. Exeter

Origin of stars and their planetary systems
Mac Master University, June 2012
Field: Resolved objects IMF down to the HB limit

1 M$_{\text{Sol}}$ 0.1 M$_{\text{Sol}}$

Kroupa '01
Chabrier '03
Salpeter
Field: Resolved objects IMF down to the HB limit

- **Salpeter**
- **Kroupa ’01**
- **Chabrier ’03**
- **Chabrier ’05**

The diagram shows the mass function of stars with a logarithmic scale on the x-axis for mass (in units of $M_{\odot}$) and a linear scale on the y-axis for the log of the number of stars per log unit of mass. The curves represent different mass functions: present, Salpeter, Kroupa’01, Chabrier’03, and Chabrier’05. The mass range is from $1 M_{\odot}$ to $0.1 M_{\odot}$.
\[ n(T_{\text{eff}}) \]

\[ n(M_J) \]

\[ \log n \left( \frac{\text{[100K]}}{} \right) \]

\[ T_{\text{eff}}[\text{K}] \]

\[ M_J \]

- Reid et al. '04
- Burgasser '04
- Burningham et al. '10
- Gizis et al. '00
- Metchev et al. '08
- Reylé et al. '10

\[ \text{CFHBS} \]

\[ \text{Allen et al. '05} \]

\[ \text{Reid et al. '04} + \text{Cruz et al. '07} \]

\[ \text{Burgasser '04} \]

\[ \text{Burningham et al. '10} \]
$n(T_{\text{eff}})$

$\log n \ [100K]$

objects
systems

$L$

$T$

$Y$

$n(M_J)$

$\log n \ [M_J]$

$2500$ $2000$ $1500$ $1000$ $500$

$T_{\text{eff}} [K]$

$5$ $10$ $15$

$M_J$

Reid et al. ‘04
+ Cruz et al. ‘07
Burgasser ‘04
Burningham et al. ‘10
Gizis et al. ‘00
Metchev et al. ‘08
Reylé et al. ‘10
Kirkpatrick et al.’12

Reylé et al. ‘10 CFHBS
Allen et al. ‘05
Reid et al. ‘04
+ Cruz et al. ‘07
Burgasser ‘04
Burningham et al. ‘10
\[ n(T_{\text{eff}}) \]

\[ n(M_J) \]

\[ \log n \ [\text{}/100\text{K}] \]

\[ \log n \ [\text{}/M_J] \]

2500 2000 1500 1000 500

2500 2000 1500 1000 500

Friday, 10 August, 12
\[ n(T_{\text{eff}}) \]

\[ n(M_J) \]

Adapted from Reid et al. '04, Cruz et al. '07, Burgasser '04, Burningham et al. '10, Burningham et al. '10, CFHBS, Allen et al. '05, Reid et al. '04, Cruz et al. '07, Burgasser '04, Kirkpatrick et al. '12, Gixis et al. '00, Metchev et al. '08, Reylé et al. '10, CFHBS.
Caution: (i) completeness, (ii) contamination, (iii) distances to get V, (iv) Malmquist bias, (v) binaries
Young clusters and SFR: system IMF across the HB limit

- Stars
- Brown dwarfs

Field system IMF
Young clusters and SFR: system IMF across the HB limit

Field system IMF

Friday, 10 August, 12
Combined analysis of 7 SFR's

**star/BD ratio in the 7 clusters consistent with the same underlying IMF**

variations in this ratio between clusters consistent with being drawn from the C05 IMF
Excess of very-low-mass BDs?

Sumi et al. ’11

5 events!
Conclusion 1

- IMF similar between the **field** and **young clusters/SFR's** (within some scatter $<3\sigma$) consistent with the same underlying IMF

- No obvious discontinuity near the HB limit

- No (or at least very weak) dependence on the environment: $N_{BD}/N_* \sim 1/3 - 1/4$

- WISE: minimum mass for BDs $> 0.01 M_{\odot}$ ruled out !!
Brown dwarf formation

Disk fragmentation
Vorobyov & Basu; Stamatellos & Whitworth; Bate

Accretion - ejection
Reipurth & Clarke; Bate, Bonnell

Gravo-turbulent fragmentation
Padoan & Nordlund; Hennebelle & Chabrier
- Disk massive and cool enough to become gravitationally unstable, according to the Toomre and Gammie criteria

\[ Q = \frac{c_s \kappa}{\pi G \Sigma} < 1 \]

\[ t_{cool} \lesssim \xi \kappa^{-1} \approx \frac{P_{rot}}{2} \]
For large $\mu$, a centrifugally supported structure forms (Machida et al. '04; Hennebelle & Teyssier '07; Price & Bate '07; Hennebelle & Ciardi '09; Commerçon et al. '10).
Low magnetic fields allow disk formation but the disk is stabilized and does not fragment.

Machida et al. '04; Hennebelle & Teyssier '07; Price & Bate '07; Hennebelle & Ciardi '09; Commerçon et al. '10
\( \mu = 5 \)

\( \mu = 2 \)

\( \mu = 1.25 \)

Hennebelle & Teyssier 2007
With stronger fields, no centrifugally supported disk forms, making rotationally driven fragmentation even more problematic (talk by Commerçon)
With stronger fields, no centrifugally supported disk forms, making rotationally driven fragmentation even more problematic (talk by Commerçon)

Machida et al. ’11, Dapp & Basu’11 (2D): resistive MHD: smaller disks than in unmagnetized case
Li,Z-Y et al’11 (2D): moderate B suppresses disk f’n/frag’n in the presence of ambipolar diffusion.

Need sufficient resolution crucial to avoid numerical reconnection (spurious flux loss)!
Comparison of the PdBI maps with MHD simulations
Maury et al. 2010; see also Stamatellos, Maury et al. ’11

Hydrodynamical simulations produce too much extended (+ multiple) structures if compared to the observations.

Hennebelle & Teyssier (2008)
MHD simulations:
produce PdB-A synthetic images with
typical FWHM ~ 0.2” - 0.6”

Similar to Class 0 PdB-A sources observed!

need B to produce compact, single PdB-A sources.
Comparison of the PdBI maps with MHD simulations

Maury et al. 2010; see also Stamatellos, Maury et al. ’11

Hydrodynamical simulations produce too much extended (+ multiple) structures if compared to the observations.

MHD simulations ?

Hennebelle & Teyssier (2008)
MHD simulations:
produce PdB-A synthetic images with
typical FWHM ~ 0.2” - 0.6”

Similar to Class 0 PdB-A sources observed!

need B to produce compact, single PdB-A sources.

Massive (hydro) disks prone to fragmentation not observed!
Isolated, massive, compact ($R_{\text{out}} \sim 20$ AU) disk around class 0 consistent w/ MHD disks!
Constraints on BD ejection after disk instability (Basu & Vorobyov ’12): **magnetic field**

No B: no outflow

B: outflow + magnetic breaking (Commerçon et al. ’10; Machida et al. ’11; Machida & Matsumoto ’11)
Constraints on disk instability from class-0 disks

Class-0 lasts $\sim 10^5$ yr (Evans et al., Enoch et al.)

$\Rightarrow$ most Class-0 objects should have massive disks: not observed!

No B: no outflow
B: outflow + magnetic breaking (Commerçon et al. ’10; Machida et al. ’11; Machida & Matsumoto ’11)

Constraints on BD ejection after disk instability (Basu & Vorobyov ’12): magnetic field
Low-mass binaries with BD-mass companions

e.g. BD LHS6343c (Johnson et al. 2010) (other examples (e.g. Joergens))

\[ M_A = 0.37 \, M_{\text{sol}} \]
\[ M_C = 0.063 \, M_{\text{sol}} \]
\[ M_{\text{DISK}} \approx 0.04 \, M_{\text{sol}} \]

not enough mass in the disk to form LHS6343c formation by disk fragmentation

Constraints on disk instability from class-0 disks

**Class-0 lasts \( \sim 10^5 \, \text{yr} \)** (Evans et al., Enoch et al.)

\[ \Rightarrow \text{most Class-0 objects should have massive disks: not observed!} \]

Constraints on BD ejection after disk instability (Basu & Vorobyov ’12): magnetic field

No B : no outflow

B : outflow + magnetic breaking (Commerçon et al. ’10; Machida et al. ’11; Machida & Matsumoto ’11)

**Magnetic field**

No B : no outflow

B : outflow + magnetic breaking (Commerçon et al. ’10; Machida et al. ’11; Machida & Matsumoto ’11)
Low-mass binaries with BD-mass companions
e.g. BD LHS6343c (Johnson et al. 2010) (other examples (e.g. Joergens))
\[ M_A = 0.37 \, M_{\text{sol}} \]
\[ M_C = 0.063 \, M_{\text{sol}} \]
\[ M_{\text{DISK}} \approx 0.04 \, M_{\text{sol}} \]

not enough mass in the disk to form LHS6343c formation by disk fragmentation

Constraints on disk instability from direct imaging
Lafrenière et al. (2010), Johnson et al. (2010), Janson et al. (2011, 2012)
(+ talks by M. Liu + M. Bonavita + Bowler)
archival data from the Gemini Deep Planet Survey:
statistics of companions around 85 ABFGKM stars in disks from 5 to 700 AU
companion frequency <10% at 99% C.L.

Constraints on BD ejection after disk instability (Basu & Vorobyov ’12): magnetic field

No B : no outflow
B : outflow + magnetic breaking (Commerçon et al. ’10; Machida et al. ’11; Machida & Matsumoto ’11)

Class-0 lasts ~ 10^5 yr (Evans et al., Enoch et al.)

=> most Class-0 objects should have massive disks: not observed!
EJECTION, COMPETITIVE ACCRETION

- Collapse of a cloud -> starts forming small N-body clusters of small ($\sim 10^{-3}$ $M_{\text{sol}}$) gravitationnally bound entities

- then accrete mass, $\dot{M} \propto M^2$ (Bondi-Hoyle) or $\dot{M} \propto M^{1.5}$ (tides)

- dynamical interactions responsible for merging (-> high-mass stars) or ejection (LMS/BD)

- dynamical interactions are essential to build the IMF
- all stars form in clusters
- the IMF is determined by the gas-to-star conversion (no correspondance with the CMF)
Constraints on competitive accretion: 1) are the simulations realistic?

\[ L = 0.4 \text{ pc} ; \  n \sim 10^5 \text{ pc}^{-3} ; \ \text{Mach}# = 14 \]
Constraints on competitive accretion: 1) are the simulations realistic?

- 50x denser and 5x more turbulent than (observed) Larson’s relations!

\[ \bar{n} = (d_0 \times 10^3 \text{ cm}^{-3}) \left( \frac{L}{1 \text{pc}} \right)^{-0.7}, \quad V_{\text{rms}} = (u_0 \times 0.8 \text{ km s}^{-1}) \left( \frac{L}{1 \text{pc}} \right)^n. \]

Falgarone et al. ’00

L=0.4 pc; \ n \sim 10^5 \text{ pc}^3; \ \text{Mach#} = 14
Bate '11: fragmentation of a cloud w/ radiative feedback

L = 0.4 pc; \( n \sim 10^5 \) pc\(^{-3}\); Mach# = 14

+ no turbulent compressive mode (Federath et al; Hennebelle & Chabrier '09)
+ uniform initial density (Girichidis et al.)
+ no B
+ stellar feedback underestimated

\[ \bar{n} = (d_0 \times 10^3 \text{ cm}^{-3}) \left( \frac{L}{1\text{ pc}} \right)^{-0.7}, \quad V_{\text{rms}} = (u_0 \times 0.8 \text{ km s}^{-1}) \left( \frac{L}{1\text{ pc}} \right)^{n}. \]

Falgarone et al. '00

\sim 50x denser and 5x more turbulent than (observed) Larson's relations!

\Rightarrow \textbf{overfavor dynamical int’ns} !!
Constraints on competitive accretion: 1) are the simulations realistic?

\[ \bar{n} = (d_0 \times 10^3 \text{ cm}^{-3}) \left( \frac{L}{1 \text{ pc}} \right)^{-0.7}, \quad V_{\text{rms}} = (u_0 \times 0.8 \text{ km s}^{-1}) \left( \frac{L}{1 \text{ pc}} \right)^{\eta}. \]

\sim 50x denser and 5x more turbulent than (observed) Larson’s relations!

\Rightarrow \text{overfavor dynamical int’ns} !!

+ no turbulent compressive mode (Federath et al; Hennebelle & Chabrier ’09)
uniform initial density (Girichidis et al.)
no B
stellar feedback underestimated

IMF set up at the very begining of the simulation brings support to the gravo-turbulent scenario!
Bayo et al. '11: radial dist’n of stars and BDs in Lambda-Ori

No difference in the distributions of stellar and substellar members

Members confirmed spectroscopically!
Marsh et al. ’10: radial dist’n of stars and BDs in rho-Oph
Constraints on ejection scenario: 3) timescale argument


\[ \sigma \sim 0.4 \text{ km/s} \]

\[ \text{collapse} \ll \text{collisions} \]

suggest little dynamical evolution during prestellar core formation

for nearly isothermal filaments \((\gamma \leq 1)\):

\[ \text{ff (cores)} \ll \text{collapse (filaments)} \]

Kawachi & Hanawa ’98
- how do you preserve the correspondence between CMF and IMF?  
   answer: deny it!

- how do you end up having a universal IMF? (Bate 2009: feedback from LMS leads to a narrow range of Jeans mass in the irradiated gas)

- how do you produce the IMF in low-density environments (e.g. Taurus)?

- how do you preserve disks, outflows in ejected embryos (proto-BDs)?

- all stars must form in clusters: contradicts obs (Bressert '10, '12)  
  + formation of isolated massive stars (Bontemps et al. ’10, Bestenlehner et al. ’11, Bressert ’12)  
  + formation of isolated proto-BDs (Palau et al. 12)
Gravoturbulent Fragmentation

- Large-scale turbulence (density PDF lognormal) sets up a lognormal distribution of overdense regions at all scales in the cloud
  -> leads to the CO clump dist’n (can be filamentary, Inutsuka ’01)

- Virial: regions $M(R)$ with $|E_{\text{grav}}(R)| > (E_{\text{th}}+E_{\text{rms}}(R)+E_{\text{mag}})$ collapse
  (introduces a scale dependence)
  -> leads to the core mass function (CMF)

- magneto-centrifugally outflows expel ~30-50% of the mass
  -> leads to the star mass function (IMF)

• turbulence sets up the density fluctuations at the very early stages of star formation: «turbulent Jeans mass»
• the IMF derives from the CMF and is imprinted in the very cloud conditions ($<n>$, T, Mach)
\[ \bar{n} = (d_0 \times 10^3 \text{ cm}^{-3}) \left( \frac{L}{1 \text{ pc}} \right)^{-0.7}, \quad V_{\text{rms}} = (u_0 \times 0.8 \text{ km s}^{-1}) \left( \frac{L}{1 \text{ pc}} \right)^\eta. \]

Chabrier system IMF

HC analytical IMF

\( M \sim 7 \)

\( M \sim 5 \)

Hennebelle & Chabrier ’08, ’09
Chabrier & Hennebelle ’11
\[ \log \Sigma \]

\[ L_{\text{cloud}} \text{(pc)} \]

\* Lada et al. ’10

\[ \square \] Evans et al. ’09

+ Heiderman et al. ’10

Gutermuth et al. ’11

Hennebelle & Chabrier 2011, 2012

Friday, 10 August, 12
Is the IMF correlated or not with the CMF?

Smith et al. 2009: frag’n of a MC -> bound cores
-> sink particles (proxy of stellar masses)

\[ \sigma = \frac{M_{\text{core}}}{3} \]

\[ x = M_{\text{sink}} \]

\[ p(M_{\text{core}}) \propto m^{-2.35} \]

\[ p(M_{\text{sink}}) \propto \exp \left\{ -\left( x - \mu \right)^2 / 2\sigma^2 \right\} \]

\[ \mu = \epsilon \cdot M_{\text{core}} \]

\[ \sigma(M) = \langle M \rangle^2 - \langle M^2 \rangle \]

Is the IMF correlated or not with the CMF?

Smith et al. 2009: frag’n of a MC -> bound cores
-> sink particles (proxy of stellar masses)

\[ \sigma = \frac{M_{\text{core}}}{3} \]

\[ x = M_{\text{sink}} \]

Smith et al. ‘09

\[ p(M_{\text{core}}) \propto m^{-2.35} \]
\[ p(M_{\text{sink}}) \propto \exp \left[-\left(x - \mu\right)^2 / 2\sigma^2\right] \]

\[ \mu = \epsilon \cdot M_{\text{core}} \]
\[ \sigma(M) = \langle M \rangle^2 - \langle M^2 \rangle \]

consistent w/ no or low observed fragmentation of cores

Bontemps et al. ’10, Longmore et al. ’11 + talk by Schnee
Turbulent Jeans mass

Hennebelle & Chabrier ’08, Chabrier & Hennebelle ’11

\[ M^\text{turb}_J(R) = \frac{V_{\text{rms}}^2}{3G} R = \frac{V_0^2}{3G} \left( \frac{R}{1\text{ pc}} \right)^{2\eta} R \]

simu: Schmidt et al. ’10
Turbulent Jeans mass

Hennebelle & Chabrier ’08, Chabrier & Hennebelle ’11

\[ M_{J}^{\text{turb}}(R) \equiv \frac{V_{\text{rms}}^2}{3G} R = \frac{V_{0}^2}{3G} (\frac{R}{1 \text{ pc}})^{2n} R \]

simu: Schmidt et al. ’10

Timescale problem

Thermal Jeans mass: \( M \sim M_J \propto C_S^3 / \sqrt{\rho} \Rightarrow \tau_{ff} \propto M \)

Turbulent Jeans mass: \( M_{J}^{\text{turb}} \propto V_{\text{rms}}^3 / \sqrt{\rho} \Rightarrow \tau_{ff} \propto M^{1/4} \)

obs. André et al. ’07

Friday, 10 August, 12
Turbulent Jeans mass

Hennebelle & Chabrier ’08, Chabrier & Hennebelle ’11

\[ M_{J}^{\text{turb}}(R) = \frac{V_{\text{rms}}^2}{3G} R = \frac{V_0^2}{3G} \left( \frac{R}{1 \text{ pc}} \right)^{2\eta} R \]

simu: Schmidt et al. ’10

Timescale problem

Thermal Jeans mass : \( M \sim M_J \propto C_S^3/\sqrt{\rho} \Rightarrow \tau_{ff} \propto M \)

Turbulent Jeans mass : \( M_J^{\text{turb}} \propto V_{\text{rms}}^3/\sqrt{\rho} \Rightarrow \tau_{ff} \propto M^{1/4} \)

Position of the peak of the IMF

\[ M_{\text{peak}} \propto M_J \times \frac{1}{(1 + b M^2)^{3/4}} \propto \rho^{-1/2} M^{-3/2} \]

\[ \rho \propto L^{-a} \quad \langle V_{\text{rms}} \rangle \propto L^\eta \quad \eta \approx 0.4 \quad a \approx 0.7 - 1.0 \]

\[ \Rightarrow M_{\text{peak}} \sim M_c^{0.1-0.2} \]
Gravo-turbulent fragmentation

- still a (analytical) theory, simulations of 2nd core under way
  (Vaytet et al., Masson et al., Inutsuka et al.)

- supported by IMF (at least partly) determined by the prestellar Core MF
  (André et al. 2010 HERSCHEL)

- can lead to binary properties consistent w/ observations (Jumper & Fisher ’12)

- emerging observations of isolated pre-BD and protoBD cores
  VeLLO L1148–IRS (Kauffmann et al. ’11); IRAS 16253-2429 (Wiseman et al.)
  J042118 + J041757 1-5 M_{Jup} (Palau et al. ’12)
- **Gravo-turbulent fragmentation**

- still a (analytical) theory, simulations of 2nd core under way
  (Vaytet et al., Masson et al., Inutsuka et al.)

- supported by IMF (at least partly) determined by the prestellar Core MF
  (André et al. 2010 HERSCHEL)

- can lead to binary properties consistent w/ observations (Jumper & Fisher ’12)

- emerging observations of isolated pre-BD and protoBD cores

  - VeLLO L1148–IRS (Kauffmann et al. ’11); IRAS 16253-2429 (Wiseman et al.)
  - J042118 + J041757  1-5 M\textsubscript{Jup}  (Palau et al. ’12)
  - Oph B-11  30 M\textsubscript{Jup}  <460 AU  n\textasciitilde10\textsuperscript{7}-10\textsuperscript{8} cm\textsuperscript{-3} (André et al. ’12)
Young BDs vs young star properties

- Same radial velocity dispersion
- Same spatial distribution in young clusters
- Consistent with the same IMF
- Wide binary BDs
- Accretion + disk signature (large blue/UV excess, large asymmetric emission lines, $H\alpha$
  => natural extension of CTTS
- Disk fraction around BDs ~40-60% similar to stars
- Timescales for accretion around BDs ~similar to stars ~1-10 Myrs
- Presence of outflows
- Observations of isolated proto-BDs and pre-BD cores

See also. Luhman et al. ’07
same radial velocity dispersion
same spatial distribution in young clusters
consistent with the same IMF
wide binary BDs
accretion + disk signature (large blue/UV excess, large asymmetric emission lines, Hα) => natural extension of CTTs
disk fraction around BDs ~40-60% similar to stars
timescales for accretion around BDs ~similar to stars ~1-10 Myrs
presence of outflows
Observations of isolated proto-BDs and pre-BD cores

BD and star formation: common mechanism
Ejection, disk frag’n, photoevaporation might play some role but are not essential in making it possible for BDs to form

see also. Luhman et al. ’07
Chabrier & Hennebelle '10

Chabrier system IMF

HC analytical IMF
Thies & Kroupa 2008:
 discontinuity between the stellar and the BD IMF
Thies & Kroupa 2008: discontinuity between the stellar and the BD IMF

\[ \frac{dn}{dm} \propto m^{-\alpha} \quad \alpha = 0.3 - 1 \]
Multiplicity frequency in the stellar and substellar regime
Observations and statistical properties of multiple Systems

About 50% of the stars are binaries (Duquenoy & Mayor 91) There are evidences that the fragmentation occurs very early when the star is still accreting.

Evidences for fragmentation in the Class0 objects IRAS4A (Observations realised with the BIMA interferometer)

Multiple embedded Young stellar objects in ρOph and Serpens

Looney, Mundy, Welch (2000)

Duchêne et al. 2003
Chabrier system IMF
Chabrier system IMF

Mach number

thermodynamics of the gas