The dependence of star cluster formation on initial conditions

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Stellar properties do not greatly depend on initial conditions

- Little evidence for variation of the Galactic IMF
  - Bastian, Covey & Meyer (2010)

- Little evidence for systematic variations of multiplicity properties
  - Multiplicity of wide systems tends to be
    - Lower at old ages and/or in dense clusters (Duchene & Kraus (2013) and references therein)
    - Not obviously dependent on stellar density - Taurus exception (King et al. 2012a)
  - Separation distributions
    - Evidence for truncation in dense clusters (e.g. Scally, Clarke & McCaughrean 1999; Reipurth et al. 2007)
    - But indistinguishable over at most separations in different regions (King et al. 2012b)
(Turbulent) semi-analytical theories of IMF

- Tend to predict that the IMF depends on
- Mean Jeans mass (i.e. density and temperature)
- Turbulent Mach number (more turbulent produces broader range of stellar masses)
Numerical simulations

- Simplest hydrodynamical simulations also predict an IMF with a characteristic stellar mass than scales with the typical Jeans mass
- Include gravity, hydrodynamics and a simple equation of state
- Klessen, Burkert & Bate (1998); Bate & Bonnell (2005); Bate (2005, 2009c)
- Jappsen et al. (2005); Bonnell, Clarke & Bate (2006)
Competitive accretion the IMF

Competition between accretion and ejection (Bate & Bonnell 2005)

Jeans Mass

Number of Stars/Brown Dwarfs

1000

100

10

1

0.1

0.01

0.1

1

10

100

1000

Mass [M_☉]

Ejection
Reipurth & Clarke (2001)
Bate et al. (2002)

Competitive Accretion
Bonnell et al. (1997, 2001)
Why do observed stellar properties not seem to depend on initial conditions?

- Either initial conditions do not vary much, or compensate each other
  - Hennebelle & Chabrier (2008, 2009) - appealing to Larson’s laws, when Jeans mass increases, Mach number increases so may offset each other
  - Hennebelle (2012) - more detailed compensation between density, velocity dispersion and temperature

- Or star formation process may be self-regulating
  - Physics is must be more complicated than just gravity + hydrodynamics + simple equation of state
    - e.g. Protostellar/stellar feedback, Magnetic fields
Self-regulation via protostellar interactions

- Gravitational fragmentation of structured molecular gas to form stellar groups
  - Exactly how the structure arises may not be so important (Bonnell et al. 1997-2001; Klessen et al. 1998-2001; Bate 2009c)

- Dissipative dynamical interactions between accreting protostars
  - Gives an IMF-like mass distribution (competitive accretion), but depends on global Jeans mass (Bate & Bonnell 2005; Jappsen et al. 2005, Bonnell et al. 2006)
  - Leads to observed multiplicity fractions & properties of multiple systems (Bate 2009a, 2012)

- Radiative interactions (feedback) between accreting protostars
  - Enables the production of an (almost) invariant IMF (Bate 2009b)

- All three together can reproduce observed stellar properties
  - Bate (2012)
When does competitive accretion operate?

- Protostellar seeds in a (uniform) gas reservoir
  - Bonnell et al. (1997, 2001)
- Nonlinearly structured gas (no initial velocities)
  - Klessen et al. (1998); Klessen & Burkert (2000, 2001)
- Strong turbulence (both decaying and large-scale driven turbulence)
  - Klessen 2001; Bate et al. (2003-2005); Bonnell et al. (2003-2010); Bate (2009-2012)

- What doesn’t work?
  - No structure or turbulence (e.g. uniform sphere)
  - Small-scale turbulent driving (Klessen 2001)
  - Centrally-condensed initial conditions resist fragmentation (Girichidis et al. 2011), especially with radiative feedback (Krumholz et al. 2011)

Klessen, Burkert & Bate (1998)
Bate 2009a: 500 $M_\odot$ cloud with decaying turbulence, 35 million SPH particles
Follows binaries to 1 AU, discs to ~10 AU
Forms 1253 stars and brown dwarfs - best statistics to date from a single calculation
**Multiplicty as a Function of Primary Mass**

- Dissipative N-body interactions naturally produce a multiplicity that increases with primary mass.
- In binary-single or multiple-multiple encounters, low-mass objects tend to lose companions and high-mass objects tend to retain or gain.

![Diagram](image.png)

- Multiplicity fraction = \((B+T+Q) / (S+B+T+Q)\)
Stellar Mass Distribution

- Competitive accretion/ejection gives
  - Salpeter-type slope at high-mass end
  - Low-mass turn over
- >6 times as many brown dwarfs as a typical star-forming region
  - Not due to sink particle approximation - results almost identical for different sink parameters
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CONSTELLATION is a European Commission FP6 Marie Curie Research Training Network involving a large number of European astronomy institutions who will be training young scientists through research into the origin of stellar masses. More detail on the network and its aims can be found here.

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CONSTELLATION will employ 17 young researchers during its 4-year programme (December 2006 to November 2010). Currently, we are reviewing applications received prior to May 31st 2007 to fill:

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BBB2003: Typical molecular cloud
Jeans mass $1 \, M_\odot$, Opacity limit $3 \, M_J$, $P(k) \propto k^{-4}$

B2009b (BBB2003, but with Radiative Transfer)

http://www.astro.ex.ac.uk/people/mbate
Bate 2009b: Typical cloud: Jeans mass $\sim M_\odot$, $P(k) \propto k^{-4}$

with Radiative Transfer

Log Column Density

Mass weight temperature (Log 9-100 K)

http://www.astro.ex.ac.uk/people/mbate
Radiative Feedback and the IMF

- Radiative feedback reduces the number of objects by factors of 3-5
- Radiative feedback brings the star to brown dwarf ratio in line with observations
  - Observations suggest a ratio of $5 \pm 2$
    - Chabrier 2003; Greissl et al. 2007; Luhman 2007; Thies & Kroupa 2007,2008; Andersen et al. 2008
- Small simulations: 25:5 \sim 5

- Furthermore, dependence of the IMF cloud density is removed
  - K-S test on the two IMFs with radiative feedback shows them to be indistinguishable

![Diagram showing cumulative fractional number of stars versus mass with and without radiative feedback](image)
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The Apparent Invariance of the IMF

• Bate 2009b
  • In the absence of stellar feedback, cloud fragments into objects separated by Jeans length
  • Jeans length and Jeans mass smaller for denser clouds
  • But, heating of the gas surrounding a newly-formed protostar inhibits nearby fragmentation
  • Effectively increases the effective Jeans length and Jeans mass
  • Effective Jeans length and Jeans mass increases by a larger fraction in denser clouds
  • This greater fractional increase largely offsets the natural decrease in Jeans mass in denser clouds
  • Bate (2009b) show that this effective Jeans mass depends very weakly on cloud density

Low-density Cloud

Higher-density Cloud
Bate 2012: 500 M_☉ cloud with decaying turbulence
Includes radiative feedback and a realistic equation of state
Produces 183 stars and brown dwarfs, following all binaries, plus discs to ~1 AU
First Large-Scale Calculation Consistent with Wide Range of Observed Stellar Properties

- Mass function consistent with Chabrier (2005)
- Stars to brown dwarf ratio: \( \frac{N(1.0-0.08)}{N(0.03-0.08)} = \frac{117}{31} = 3.8 \)
- Multiplicity consistent with field
- Binary mass ratios consistent with field

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**Mass function**
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**Multiplicity**
- Mass ratios consistent with field
- Binary mass ratios consistent with field

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**G&K primaries**
- Number
- Mass ratio

**M-dwarfs**
- Number
- Mass ratio

**Very-low-mass**
- Number
- Mass ratio
Fig. 10. An expanded view of the approximate temperature map from Figure 9. The known cluster members and submillimetre emission regions are marked by stars and labeled. Protostar disks tend to appear hot (red), while the starless regions are clearly colder than the rest of the cloud. FP-25 appears colder than IRS 5, and IRS 7e is also colder than IRS 7w. There is no significant emission near IRS 9, located to the east of a submillimetre "hole". The Class 0 candidates, SMM 1A and SMM 1As, are clearly colder than the dominant Class I protostars and the disked objects. The very low-mass protostellar candidate, G-122, is also colder than more massive Class I sources. The secondary peak of the LABOCA map, coincident with source SMM 6 from Nutter et al. (2005), appears as a distinct region even colder than the Class 0 protostars. We take the outer disk radius to be 100 AU for the low-mass stars, and 300-400 AU for the intermediate-mass stars. The dust component of the disk is assumed to be composed of amorphous grains with similar amounts of Mg and Fe (Jäger et al. 1994; Dorschner et al. 1995). This simple dust model reproduces the strength of the silicate features very well, although we note that the main purpose of this exercise is to understand the global SED shape, and not the dust composition in the disk atmosphere. In addition, 25% of carbon has been included, with similar sized distributions as the silicate grains. In order to obtain the full disk mass, we consider a gas-to-dust ratio of 100. We assume that there is no dust temperature dependence on the grain size, and the dust grains are considered to be well mixed (i.e., without size-dependent differential settling). The stellar parameters (namely \( R^* \) and \( T_{\text{eff}} \)) were estimated by using the temperature-spectral type relation for Taurus stars (Kenyon & Hartmann 1995) and varying the radius to reproduce the total observed luminosity in the optical/near-IR. These simple models do not account for the many effects expected in protoplanetary disks (e.g. differential settling and grain growth, inside-out evolution), but our aim is to understand the global SED shape and properties of the disks. Only in cases where no reasonable fit to the observed SED could be achieved with the simplified models, we included additional parameters, specifically by considering: inclusion of large grains/removal of small grains in the dust component, modification of the inner disk rim to include an inner hole at distances larger than the dust destruction radius, and variation of the flaring and dust properties.
Dependence of Stellar Properties on Metallicity: Opacity

• Bate (2014) repeated Bate (2012), but with opacities for 3 different `metallicities’
  • Use opacities corresponding to metallicities $Z=0.01\, Z_\odot, 0.1\, Z_\odot, Z_\odot$, and $3\, Z_\odot$
  • Does NOT take into account all of the effects of reduced metallicities
    • Assumes dust cooling still dominates
    • Breaks down as gas and dust temperatures decouple
• Gas opacities from Ferguson et al. (2005)
• Each calculation produces 170 - 200 stars (733 total)
  • Look for variation of stellar properties

[Graph showing opacity vs temperature]
Dependence of Stellar Properties on Opacity

- No significant dependence of any stellar property
- Despite varying opacity by a factor of 300
- IMFs consistent with Chabrier (2005)
- Multiplicity is a strong function of primary mass
- In good agreement with observational surveys
Stellar Properties and Opacity

• If IMF is so dependent on radiative feedback, why are stellar properties so independent of opacity?

• Temperature of dust around a protostar (optically thin)

\[ T \propto L_*^{1/4} r^{-2/(4+\beta)} \]

• where \( \beta \) depends on absorption properties of dust (e.g. Ivezic & Elitzur 1997)

• If gas is

• Thermally coupled to the dust (as assumed in Bate 2014), and

• Infrared radiation is optically thin (valid or marginally valid for Bate 2014)

• Then, gas temperature around protostars does not depend on magnitude of opacity

• i.e. Effects of radiative feedback should be similar
Overall Stellar Properties

- Since the individual IMFs and multiplicities are indistinguishable, we can combine the results from the three calculations with the highest opacities (535 stars and brown dwarfs).

- Bate (2014): Best numerically-determined stellar properties to date.

- The IMF and multiplicity as a function of primary mass are indistinguishable from observations.

- Ratio of stars to brown dwarfs ~3.8:1 (c.f. Andersen et al. 2008: 5 ± 2)
Long-term Evolution?

- Hydrodynamical evolution only followed for $\sim 3 \times 10^5$ yr

- How does the cluster evolve on 10 Myr timescales?
  - Does gas dispersal unbind the cluster (only 15-38% of mass in stars)?
  - Destruction or formation of binary and multiple systems?
    - Kroupa (1995a,1995b): N-body simulations beginning with 100% binaries found many binaries were quickly destroyed
    - Is it possible to form very wide binaries in the halo of ejected stars?

- Moeckel & Bate (2010) used N-body6 code to evolve end state of Bate (2009a)’s hydrodynamical simulation to an age of 10 Myr
  - Four cases:
    - Instantaneous gas removal
    - Gas decreases to 10% after 0.3 Myr
    - Gas decreases to 10% after 1 Myr
    - No gas removal
Evolution over 10 Myr

Instantaneous Gas Removal (Moeckel & Bate 2010)
The Evolution of Cluster Structure

- **Hydrodynamical evolution**
  - Stars form along filaments in sub-clusters
  - Sub-clusters merge to form one massive cluster surrounded by a halo of ejected stars

- **N-body evolution**
  - Cluster expands by a factor of ~20 (from 0.05 pc to 2 pc - comparable to ONC)
  - More stars ejected
  - Ejected stars continue to expand

- **Quantify using Q parameter**
  - Cartwright & Whitworth (2004)
  - Q<0.8: Sub-structure / fractal
  - Q=0.8: No structure
  - Q>0.8: Density gradient or cluster/halo

![Graph showing evolution of time vs Q parameter](image)
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Lagrangian Radii

- Remnant cluster
  - Contains 30-40% of stellar mass
  - Expands from 0.05 pc to 1-2 pc over 4-10 Myr except in the case without gas removal
- Halo
  - Freely expands to >100 pc in <10 Myr
Stellar Multiplicity

- End of hydrodynamical calculation
  - Multiplicity \( (= \frac{B+T+Q}{S+B+T+Q}) \) is an increasing function of primary mass

- Evolution over 10 Myr has little impact on multiplicities
  - Primordial multiple systems formed in a cluster are naturally resistant to disruption
  - Cannot separate star formation from multiple system formation
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Separation Distributions

- Decay of high-order (quadruple) systems
- All cases, except no gas removal, form a significant number of very wide (>10^4 AU) systems (see also Kouwenhoven et al. 2010)
- Little evolution of VLM systems, except that wide (>60 AU) systems broken up
Conclusions

• Invariance of stellar properties:
  • Interstellar conspiracy or self-regulation?

• Protostellar interactions may provide self-regulation and stellar properties
  • Gravitational fragmentation of structured molecular gas to form stellar groups
  • Dissipative dynamical interactions between accreting protostars
    • Gives an IMF-like mass distribution (competitive accretion), but depends on global Jeans mass
    • Leads to observed multiplicity fractions & properties of multiple systems
  • Radiative feedback (interactions) from accreting protostars
    • Enables the production of an (almost) invariant IMF
  • All three together can reproduce observed stellar properties (Bate 2012, 2014)

• Cluster evolution
  • Star clusters may begin very dense (e.g. half-mass radii < 0.1 pc) and expand at 1-2 Myr
  • Wide binaries may form during cluster dissolution (Moeckel & Bate 2010; Kouwenhoven et al. 2010)