Competitive Accretion in Stellar Clusters

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(St Andrews)

Matthew Bate, Paul Clark, Ralf Klessen, Jim Dale
Origin of stellar masses

- **Turbulently driven fragmentation**
  - Structure in molecular clouds
  - Clump mass spectrum: IMF

- **Gravity driven fragmentation**
  - \( \sim \) thermal Jeans masses
  - Accretion in clusters produces higher masses
  - Low masses from gravity-produced dense gas

- **SPH Simulations: self-gravitating decaying turbulence**
  - \( E_{\text{kin}} \geq |E_{\text{grav}}| \)
  - No Magnetic fields
  - Some feedback!
Origin of stellar masses: context

• Need to understand SF in context of forming full IMF

• many/most stars form in clusters
  - Full IMF

• ~ All higher mass stars
  De Wit et al 2005
  - Massive stars in centre

• Binaries

• Disks

M. McCaughrean
Turbulent Fragmentation

- Produces full clump mass $m_f$
- But low masses unbound
- High-mass clumps fragment
- Star formation occurs $\sim$ Jeans Mass

Klessen et al 2005; Clark & Bonnell

Evolution towards SF

Clark & Bonnell 2005
Stability of Pipe cores

Critical BE mass corresponds to the characteristic mass of the CMF

Lada et al, submitted

Critical BE mass corresponds to the characteristic mass of the CMF

Gravitationally unbound

Fragment

Unstable

Stable
Clump velocities

- At point of first SF
- Low clump-clump vels
- After free-fall time
- ~ higher clump-clump vels

P. Clark
Characteristic stellar mass

- Simulations show masses \( \sim M_{\text{Jeans}} \).
- What sets \( M_j \)?

Thermal physics:

- Bonnell, Clarke & Bate 2006
- Larson 2005, Spaans & Silk 2000
- Jappsen et al. 2005

Bonnell, Clarke & Bate 2006
Competitive accretion

Bonnell et al 1997, 2001

- **Fragmentation down to (thermal) Jeans Mass**
  - Form as lower mass stars \( (\sim 0.5 \, M_{\text{sun}}) \)
  - Subsequent accretion forms high-mass stars

- **Accretion limited by**
  - Tidal effects
  - Gas velocities: Bondi-Hoyle

- **Stars do not have to move!**

- **Gas inflow due to cluster potential**
  - to cluster centre
  - Higher gas density:
    - Higher accretion rates

- **Requirements:**
  - \( N > 2 \) fragments
  - Common gas reservoir
The Formation of a stellar cluster

Stellar masses

10^3 M_\text{sun} in 1 pc

Forms full IMF

Mass segregated clusters

Bonnell, Bate & Vine 2003
Origin of stellar masses

Fragmentation mass
~ Jeans Mass

- Envelope mass
- Accretion from outside stellar cluster

• Massive stars form due to accretion from large-scale reservoir

Bonnell, Vine & Bate (2004)
Competitive accretion

- Accretion rates

\[ \dot{M}_{\text{acc}} = \pi \rho v R_{\text{acc}}^2 \approx \pi \rho \left( \frac{GM_*}{v^3} \right)^2 \]

All local variables

<table>
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<tr>
<th>Global Cloud</th>
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<td>( \rho )</td>
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Competitive accretion doesn’t work?

Krumholz et al 2005
Competitive accretion

Accretion rates

\[ \dot{M}_{\text{acc}} = \pi \rho v R_{\text{acc}}^2 \approx \pi \rho \left( \frac{GM_*}{v^3} \right)^2 \]

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Large range in possible \( \dot{M}_{\text{acc}} \)

Bonnell & Bate 2006
Accretion starts in small-N clusters

- Low velocity dispersion
  - Short accretion timescale

- Attain ~higher masses before $v_{\text{disp}}$ high

- Form massive stars in few $10^5$ years
GMC scale star formation

- $10^4 \, M_{\text{sun}}$ in 10 pc
- Forms $> 2500$ stars
  - Over $6 \times 10^5$ years
- Full IMF
- $1.5 \times 10^7$ SPH particles
  - On two levels
Mass resolution $\sim 0.02 \, M_{\text{sun}}$
- Sink radii 200 AU

Bound (top) and unbound (bottom) initial conditions

Bonnell, Clark & Bate 2007
Bound (top) and unbound (bottom) initial conditions

$10^4 \, M_{\text{sun}}$ in 10 pc

Clustered and distributed SF

Efficiency varies from < 1% to 20%

Universal IMF
Gas density
in 0.1 pc
$M_j \sim \rho^{-1/2}$

Clusters
Stars in 0.5 pc at point of fragmentation

Velocity
in (0.2 km/s )
relative to CoM
in 0.5 pc
Origin of stellar masses

- **Massive stars**
  - Form early at \( \sim M_J \), sit in centre of cluster
  - High accretion rates

- **Low-mass stars**
  - Form later as gas falling into cluster potential
  - High relative velocity
  - Little subsequent accretion
SF efficiencies and clustered SF

- **Bound** conditions produce **stellar clusters**
  - Relatively high efficiencies
  - 20-50 %
  - Full IMF

- **Unbound** regions produce **distributed SF**
  - Low SF efficiencies
  - Few %
  - Flat/Peaked IMF
  - No high-mass, few low mass stars
An unbound example...

KE = 2 x PE
(initially)
Isothermal
EOS

Clark, Bonnell & Klessen (2007)
Star formation efficiencies?

Naturally, more unbound clouds/regions have lower efficiencies…

\[ \alpha_{\text{kin}} = \frac{|\text{PE}|}{\text{KE}} \]

Clark et al 2007

Isothermal EOS

Barotropic EOS
As clouds become more unbound, competitive accretion is unable to create the ‘correct’ IMF.
Star formation efficiency per $t_{ff}$

- GMC simulation
- Final SFE $\sim 15\%$
- BUT
- Equal probability of observing at all stages of evolution
- Average value of SFE is then much lower
- $\sim 3\%$ SFE/$t_{ff}$
- Even for short cloud lifetimes
Winds have moderate effect on accretion rates
No winds

collimated

isotropic

isotropic

collimated

No winds
Conclusions

- **Gravity driven SF can explain IMF**
  - Competitive accretion in cluster potential:
    - Higher mass stars due to high accretion rates in cluster centres
    - Low mass stars/BDs from infalling gas into cluster
  - **Unbound clouds produce low SFEs**
    - Distributed SF
    - Abnormal IMFs
  - **Most stars must form in bound groups**
  - **Need to include all feedback processes**