The roles of thermal feedback and magnetic fields in sub-GMC star formation

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Stellar Properties

- **Initial mass function**
  - Observed to be relatively independent of initial conditions, at least in our Galaxy (Bastian, Covey & Meyer 2010)

- **Star formation rate and efficiency**
  - Observed to be 3-6% of gas mass per free-fall time (Evans et al. 2009)

- **Multiplicity**
  - Observed to be an increasing function of primary mass
  - Separations, mass ratios, eccentricities
  - High order systems (triples, quadruples)

- **Protoplanetary discs**
  - Masses, sizes, density distributions
What determines stellar properties?

- Gravitational fragmentation of structured molecular gas to form stellar groups
  - Exactly how the structure arises is probably not so important
- 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 and 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
Star cluster formation (in turbulent clouds)

- Produce large samples of stars
  - Dense cores of all masses form and evolve self-consistently from larger scale flows
  - Interactions between cores and protostellar systems naturally included

- Can be divided into two groups

- Those that resolve the opacity limit for fragmentation
  - Aim to resolve all stars and brown dwarfs, most binary and multiple systems, discs
  - Bate, Bonnell & Bromm (2002a,b, 2003); Bate & Bonnell (2005); Bate (2005, 2009, 2012); Offner et al. (2008)

- Those that do not
  - Can only try to address the origin of the IMF
  - Bonnell et al. (1997, 2001); Klessen, Burkert & Bate (1998); Klessen & Burkert (2001); Bonnell & Bate (2002); Bonnell et al. (2003); Offner et al. (2009); Urban et al. (2010); Krumholz et al. (2011)
Welcome to CONSTELLATION

Part of M16, the Eagle Nebula, in the infrared

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.

PhD and Postdoctoral Positions Available

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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- up to 5 Experienced Researcher (postdoc) positions

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Typical molecular cloud (Bate et al. 2003) Jeans mass $1 \, M_\odot$, Opacity limit $3 \, M_\odot$, $P(k) \propto k^{-4}$

Denser cloud (Bate & Bonnell 2005) Jeans mass $1/3 \, M_\odot$

Lower metallicity cloud (Bate 2005) Opacity limit $9 \, M_\odot$

Large-scale `turbulence' (Bate 2009c) $P(k) \propto k^{-6}$

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Characteristic stellar mass depends on the cloud’s mean Jeans mass (Bate & Bonnell 2005; Jappsen et al 2005; Bonnell et al. 2006)

Denser/cooler clouds produce more brown dwarfs

http://www.astro.ex.ac.uk/people/mbate
What is the Origin of the IMF?

Competition between accretion and ejection (Bate & Bonnell 2005)

Jean's Mass

Number of Stars/Brown Dwarfs

Ejection

Reipurth & Clarke (2001)

Bate et al. (2002)

Competitive Accretion

Bonnell et al. (1997, 2001)
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); 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 thermal feedback (Krumholz et al. 2011)
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
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Multiplicity as a Function of Primary Mass

- Multiplicity fraction = (B+T+Q) / (S+B+T+Q)
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Star/VLM Object Separation Distributions

Stars: binary, triple, quad separations

VLM objects: binaries, triples, quads

Median separation: 26 AU

Median separation: 10 AU
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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

![Stellar Mass Distribution Graph]

- Salpeter
- C03
- K01

\[ \text{Number} \]

\[ \text{Mass} \ [M_\odot] \]
What determines stellar properties?

- 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)
  - Leads to observed multiplicity fractions & properties of multiple systems (Bate 2009a, 2012)

- But
  - IMF depends on global Jeans mass (Bate & Bonnell 2005; Jappsen et al. 2005, Bonnell et al. 2006)
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BBB2003: Typical molecular cloud

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

BBB2003, but with Radiative Transfer

Dimensions: 82495. AU Without Radiative Feedback Time: 196935. yr

Dimensions: 82495. AU With Radiative Feedback Time: 196935. yr

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BBB2003: Typical cloud: Jeans mass $1 \, M_\odot$, $P(k) \propto k^{-4}$ with Radiative Transfer

Log Column Density

Dimensions: 5156. AU

Time: 197316. yr

Mass weight temperature (Log 9-100 K)

Dimensions: 5156. AU

Time: 197316. yr

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

- Thermal feedback reduces the number of objects by factors of 3-5
  - See also Offner et al. (2009), Urban et al. (2010)

- Thermal feedback brings star to brown dwarf ratio in line with observations
  - Observations suggest a ratio of 5 ± 2
    - Chabrier 2003; Greissl et al. 2007; Luhman 2007; Thies & Kroupa 2007,2008; Andersen et al. 2008
  - Small simulations: 25:5 ~ 5

- Furthermore, dependence of the IMF density is removed
  - K-S test on the two IMFs with thermal feedback shows them to be indistinguishable
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: $500 \, M_\odot$ 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
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. Protostars and disks stand out 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.

The disk rim at the dust destruction radius (for silicate dust, located at the distance at which the temperature reaches 1500 K), and at typical population sizes between 0.1 and 100 µm following a collisional power law distribution with exponent -3.5. 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 distribution 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_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 parameters.
Large-scale Simulations with Radiative Feedback

- Comparison of the IMFs obtained without and with radiative feedback
  - Many fewer brown dwarfs, confirming Bate (2009b), Offner et al. (2009) but better statistics
  - More stars than brown dwarfs: Ratio: $N(1.0-0.08)/N(0.03-0.08) = 117/31 = 3.8$
  - Mass function consistent with Chabrier (2005) parameterisation of the Galactic IMF
Cumulative Mass Functions

- Comparison of the IMFs
  - Left panel: Without and with thermal feedback
    - Mass function consistent with Chabrier (2005) parameterisation of the Galactic IMF
  - Right panel: with radiative feedback at four different times (indistinguishable)

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**Dependence on Thermal Feedback**

- Barotropic
  - Bate (2009a)
- Thermal Feedback
  - Bate (2012)
  - & Chabrier (2005)

**Evolution with time during calculation**

- Statistically Indistinguishable
Multiplicity with Thermal Feedback

- Multiplicity as a function of primary mass
  - Comparison with Close et al. (2003); Basri & Reiners (2006); Fisher & Marcy (1992); Raghavan et al. (2010); Duquennoy & Mayor (1991); Preibisch et al. (1999); Mason et al. (1998)
  - Multiplicities similar for low-mass stars, perhaps a little lower for intermediate masses
  - Smaller numbers, but still consistent with observations

Without Thermal Feedback

With Thermal Feedback

[Graphs showing multiplicity as a function of mass with and without thermal feedback]
Multiple Star Separations with Thermal Feedback

- Separation distributions as a function of primary mass
  - Comparison with Raghavan et al. (2010) and vlmbinaries.org
  - Stellar binaries have a broad range of separations
    - Wide multiples can be formed upon cluster dispersal (Moeckel & Bate 2010)
  - Very-low-mass binaries (binary brown dwarfs) have separations < 20 AU

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**Stellar primaries**

- Number vs. Semi-major Axis [AU]

**Very-low-mass (VLM) primaries**

- Number vs. Semi-major Axis [AU]
Binary Star Mass Ratios with Thermal Feedback

- Binary mass ratios as a function of primary mass
- Comparison with surveys of Raghavan et al. (2010), Fisher & Marcy (1992), vlmbinaries.org
- Very-low-mass objects (brown dwarfs) have near-equal masses
- More massive primaries have consistently flatter distributions

0.5 < $M_1/M_\odot < 1.2$

0.1 < $M_1/M_\odot < 0.5$

$M_1/M_\odot < 0.1$
What determines stellar properties?

- **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)

- **Thermal feedback (interactions) from accreting protostars**
  -Enables the production of an (almost) invariant IMF (Bate 2009b)

- **All three together can reproduce observed stellar properties**
  -Bate (2012)
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)

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

- All three together can reproduce observed stellar properties
  - Bate (2012)
A Predictive Theory of Star Formation

- Bate (2012) marks a turning point
  - We can finally produce realistic stellar systems

- Beginning from this point, we can now develop a predictive theory of star formation

- Initial conditions
  - Cloud structure and kinematics
  - Metallicity
  - Magnetic fields

- Environment
  - Level of external radiation (e.g. high-z, starbursts)
  - Location (e.g. outer galaxy, galactic centre)
The Dependence of Stellar Properties on Metallicity

- Much focus on the properties of Population III stars
  - Bromm et al. (1999, 2002); Abel et al. (2000, 2002); Clark et al. (2011)
  - Not directly observable

- Repeated Bate (2012), but with three different metallicities
  - Metallicities Z=0.01 \( Z_\odot \), 0.1 \( Z_\odot \), \( Z_\odot \), and 3 \( Z_\odot \) (range of 300)
  - Dust cooling still dominates - dust opacities taken to be proportional to metallicity
  - Gas opacities from Ferguson et al. (2005)
  - Each calculation produces 170 - 200 stars and brown dwarfs (733 total)
    - Look for variation of stellar properties

- Similar calculations performed by Myers et al. (2010)
  - Found no metallicity dependence, but metallicity range of only 20
  - Only \( \sim \)50 stars per calculation, did not resolve most brown dwarfs
IMF Expectations?

- No definitive observed variation of IMF with metallicity (Bastian et al. 2010)

- If IMF depends on global Jeans mass
  - Cooling less effective at low metallicity
  - Jeans mass high, stellar masses greater

- But, collapsing gas becomes optically thick later
  - Fragmentation may occur at higher densities
  - More stars, lower masses

- If depends on thermal feedback
  \[ T \propto \frac{L_*^{1/4}}{r^{2/(3+\beta)}} \]
  \[ \kappa \propto \lambda^{-\beta} \]
  - No dependence of IMF on metallicity
Multiplicity and Metallicity

- Metal deficient G- and K-stars
  - Others do not (Latham et al. 2002 (spectroscopic); Chaname & Gould 2004 (wide); Zapatero Osorio & Martin 2004; Zinnecker et al. 2004)
  - Some indicate potentially higher multiplicity (Grether & Lineweaver 2007)

- M-dwarf binaries may depend on metallicity
  - May have a lower frequency or be closer for lower metallicity
  - Riaz, Gizis & Samaddar (2008); Lodieu, Zapatero Osorio & Martin (2009)

- Brown dwarf companions to stars may be more common at higher metallicity
  - Raghavan et al. (2010)
Dependence of IMF on Metallicity

- $Z=0.01 \, Z_\odot$

- $Z=0.1 \, Z_\odot$

- $Z=Z_\odot$

- $Z=3 \, Z_\odot$
Dependence of IMF on Metallicity

- Cumulative IMFs are indistinguishable
- May be an excess of brown dwarfs for $Z=0.01 \ Z_{\odot}$
- 1.2% probability that 0.01 and 0.1 mass functions differ (about 2.5 sigma)
Dependence of Multiplicity on Metallicity

\[ Z = 0.01 \ Z_\odot \]
\[ Z = 0.1 \ Z_\odot \]
\[ Z = Z_\odot \]
\[ Z = 3 \ Z_\odot \]
Dependence of Separation on Metallicity

- The separations of stellar multiples seem to depend on metallicity
  - Metal poor systems tend to be closer
  - Median separations are 9.6 AU, 15.5 AU, 14.8 AU, 16.7 AU

- However, K-S test cannot distinguish between the 4 distributions
  - Probability of the Z = 0.01 Z⊙ and Z = 3 Z⊙ distributions being drawn from the same underlying distribution is 2.3% (about 2.3 sigma)

- There are not enough VLM binaries to test their dependence
Overall Stellar Properties

- Since the individual IMFs and multiplicities are indistinguishable we can combine the results from all four calculations (733 stars)
  - 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 ~3.3:1

Comparison with Chabrier (2005)
Overall Binary Mass Ratios

- Solar-type binaries
  - Broad range of mass ratios, perhaps too many “twins”

- M-dwarf binary
  - Rising mass ratio distribution, in good agreement with Janson et al. (2012)

- Brown dwarfs
  - Bias towards equal-masses, in good agreement with observations (VLM binary archive)

- However, K-S test cannot distinguish between the 3 distributions
Magnetic Fields?

- Magnetic fields inhibit disc and binary formation
  - Dorfi (1982); Phillips & Monaghan (1985, 1986); Hosking & Whitworth (2004); Price & Bate (2007); Hennebelle & Fromang (2008); Hennebelle & Teyssier (2008); Duffin & Pudritz (2009); Commercon et al. (2010)
  - May be less important with misaligned magnetic fields and turbulent initial conditions (Hennebelle & Ciardi 2009; Joos et al. 2012; Seifried et al. 2012)

- Star cluster formation
  - Produce structure in molecular clouds that cannot be obtained with purely hydrodynamical simulations
  - Stronger magnetic fields lead to slower star formation rates (Price & Bate 2008, 2009)
  - Magnetic fields may reduce the characteristic mass of the IMF (Price & Bate 2009; Li et al. 2010; Hocuk et al. 2012)
Density Striations Aligned with Field

- Column density striations seen in simulations and observations
- $^{12}\text{CO}$ striations aligned with magnetic field in Taurus (Goldsmith et al. 2005, 2008)
- Low-density gas in strongly magnetised turbulent cloud simulations (Price & Bate 2008)
Star Formation Rate

- Star formation rate decreases with
  - Increasing magnetic field strength
  - Radiative feedback

- Observationally
  - Evans et al. (2009)
  - Spitzer c2d survey, 5 clouds
  - \( \sim 3-6\% \text{ SFR}/t_{ff} \)

- Numerical results
  - 10-32\% SFR/t_{ff}

- Strongest field, with thermal feedback
  - \( \sim 10\% \text{ SFR}/t_{ff} \)
Magnetic Fields and the IMF

- Price & Bate (2009) found that their mean stellar mass reduced by a factor of 3 with a strong field
  - But each calculation produced less than a dozen stars
- Li et al. (2010) find their characteristic mass decreased by a factor of 3 with magnetic fields
  - and an order of magnitude with both outflows and magnetic fields
- Hocuk et al. (2012): very strong decrease in the characteristic mass with stronger magnetic fields on star formation near a black hole

![Graph showing stellar mass distributions for different models](image)
Collapse of magnetised cores and jets/outflows

Price, Tricco, Bate (2012)
Conclusions

- **2012: Star formation simulations can finally produce realistic stellar populations**
  - Stellar properties determined by fragmentation followed by dynamical and thermal interactions between protostars
  - Require structured initial conditions, gravity, fluid dynamics and radiative transfer
- **Stellar properties do not vary strongly with metallicity**
  - In the dust dominated regime (0.01 - 3x Solar)
  - Hints that metal poor systems may have more brown dwarfs and closer multiples
- **Future calculations will**
  - Investigate effects of magnetic fields and outflows
  - Lead to a predictive theory of star formation