The origin and variation of the stellar initial mass function

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What determines stellar properties?

- Gravitational fragmentation of structured molecular gas to form stellar groups
  - Exactly how the structure arises is probably not so important (see Bate 2009c; Bertelli Motta et al. 2016; Liptai et al. 2016)

- 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
Competitive accretion & dynamical interactions

- Larson (1978)
  - “…the final mass spectrum is determined at least in part by accretion processes and the competition between different accreting objects.”

- Zinnecker (1982)
  - “…a simple analytic accretion model for the protostellar mass spectrum ... in which protostellar cores compete for the accretion of the gas…”
  - Competition for mass as $\dot{M} \propto M^2$ produces a Salpeter-like mass function
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 radative feedback and a realistic equation of state
Produces 183 stars and brown dwarfs, following all binaries, plus discs to $\sim$1 AU
Bate (2012): 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
The major conclusions of this work are as follows:

- The observed decrease of mass between Class 0 and Class I protostars, and further to Class II, shows that a significant fraction of dust is dispersed or incorporated into larger bodies. If the latter scenario is considered, the amount of dust available for planet formation is estimated to be about 248 M⊙.
- In Perseus, the radio luminosity from the protostars is weakly correlated with the mass, indicating that the free-free emission is consistent with moderately optically thick thermal free-free emission. The C-band spectral index shows no significant variation.
- Examples of systems where brighter Ka-band component appears fainter in C-band are noted.
- Protostellar systems from the calculation analysed in this paper (solid line) show a range of disc masses, with Class II objects having masses up to a significant fraction of the star's mass.
- The cumulative distribution of disc dust mass is plotted for the discs of Class II objects observed in different star-forming regions. The simulated discs contain a similar mass fraction to the other observational surveys and the number of unresolved discs in the ONC.
- The radii of the gas discs in Upper Scorpius are a factor of two higher than those in Lupus studied by Ansdell et al. (2016), and two distributions derived from the simulations of two or three. On the other hand, the dust masses derived by Ansdell et al. (2016) are typically a factor of two higher than those derived from the simulation.
- Wherever Ansdell et al. (2016) assumed a constant temperature of 20 K, the dust discs in the hydrodynamical calculation are resolved. Overall, there is currently uncertainty in dust temperatures of two or three. Andrews et al. (2013) by (Ansdell et al. 2016), Lupus (Ansdell et al. 2016), Taurus (Andrews et al. 2009, 2010), and for discs of Class II objects observed in different star-forming regions. The reanalysis of Taurus data by Andrews et al. (2013) gives characteristic radius that contains a similar mass fraction to the other observational surveys.

CONCLUSIONS

The cumulative distributions of the disc dust mass for the discs of Class I objects observed in different star-forming regions are shown. The radii of the gas discs (as is typical for the isolated systems) are larger than those in Lupus, with a factor of 2.5 orders of magnitude more massive than those in Taurus and Lupus, and 2 orders of magnitude more massive than those in Upper Sco. The Upper Sco. stellar systems contain 9 systems in other regions or in isolation, while the disc radii range from 200 au to 600 au, and those in Taurus are smaller than those in the ONC which we have already used to plot the cumulative distribution in the upper panel. A relation between the two evolutionary stages indicating that strength and nature of the resolved discs in the hydrodynamical calculation is somewhat steeper. However, the question becomes how to deal with non-detections and upper limits in the observational surveys. From the simulation, we plot the distribution obtained using the dust in four of the seven cases. At face value, the four distributions derived from the simulations of two or three. On the other hand, the dust masses derived by Ansdell et al. (2016) are typically a factor of two higher than those derived from the simulation. Wherever Ansdell et al. (2016) assumed a constant temperature of 20 K, the dust discs in the hydrodynamical calculation are resolved. Overall, there is currently uncertainty in dust temperatures of two or three. Andrews et al. (2013) by (Ansdell et al. 2016), Lupus (Ansdell et al. 2016), Taurus (Andrews et al. 2009, 2010), and for discs of Class II objects observed in different star-forming regions. The reanalysis of Taurus data by Andrews et al. (2013) gives characteristic radius that contains a similar mass fraction to the other observational surveys.

https://www.astro.ex.ac.uk/people/mbate/
A Predictive Theory of Star Formation

- Now that we can produce realistic stellar populations
  - Bate (2012)

- the challenge is to 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)
Does the IMF vary with metallicity?

- **Sub-solar metallicities**
  - Molecular gas generally hotter (reduced line-cooling and dust cooling)
  - Jeans mass larger ($\propto T^{3/2}$)
  - Characteristic stellar mass larger?

- **Sub-solar metallicities**
  - Reduced opacity
  - Collapsing gas optically thin and able to cool quickly at higher densities
  - Jeans mass smaller ($\propto 1/\sqrt{\rho}$)
  - Characteristic stellar mass smaller?

- **Past calculations varied only opacities**
  - Myers et al. (2011); Bate (2014) - no strong dependence of IMF on opacity
Radiative transfer with separate gas, dust, radiation temperatures (Bate & Keto 2015)
Gas Temperature with Different Metallicities
Dependence of the mass function on metallicity

- Results at end ($t_{ff}=1.20$):
  - $Z=0.01 \ Z_{\odot}$: 142 stars and BDs
  - $Z=0.1 \ Z_{\odot}$: 174 stars and BDs
  - $Z=Z_{\odot}$: 255 stars and BDs
  - $Z=3 \ Z_{\odot}$: 258 stars and BDs

- Median masses range from $0.163-0.195 \ M_{\odot}$ (Chabrier 2005 has $0.20 \ M_{\odot}$)

- Low metallicity seems to produce slightly more brown dwarfs
  - Reduced opacities: greater cooling at higher densities and more small-scale fragmentation
Dependence of multiplicity on metallicity

- No strong dependence of overall multiplicity
- Multiplicity strongly increases with primary mass
- Indications that
  - Separations may decrease with decreasing metallicity
  - see Moe & Kratter (2018) for observational evidence
- No significant difference in binary mass ratio distributions
Conclusions

- **Characteristic stellar mass depends**
  - More on small-scale thermodynamics (thermal feedback) and dynamical interactions
  - Than large-scale initial density, temperature, turbulence, and magnetic fields
  - Calculations including thermal feedback can reproduce observed stellar properties (Bate 2012, 2014; Krumholz et al. 2012)

- **Working to predict the variation of stellar properties**
  - Stellar properties are resilient to changes in initial conditions and environment
  - However, small changes in IMF and multiple star properties starting to be identified
    - Low-mass stellar mass distribution has **VERY** weak dependence on metallicity ($Z \geq 0.01 \ Z_\odot$)
    - Weak dependencies on cloud density and level of interstellar radiation field
  - Still need to
    - Probe stellar properties over a much broader range of initial conditions
    - Extend to massive stars