Review of Low-Mass SF Simulations

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OutlIne

• Degrees of Freedom
• Codes
• Selected Highlights
• Metrics of Comparison
• Frontiers
Simulation Dimensions

Physics
- Astrochemistry
- Radiation
- Heating, pressure, ionization
- Magnetic Fields
- Ohmic diss., AD, reconnection
- Gravity
- Turbulence

High-mass

Is non-ideal necessary?

Dynamically, no.
Observationally, yes!

“Degrees of Freedom”

Spatial Resolution

Time
STAR FORMATION:
Simulation Dimensions

- Physics
- Spatial Resolution
- Time

“Degrees of Freedom”

- 10 pc
- 1 pc
- 0.1 pc
- 100 AU
- 10 AU
- 1 AU
- 0.1 AU
- 0.01 AU

Galaxy Sims.

Individual Star
Simulation Dimensions

Other Considerations:
- Statistics (1 -1000 *)
- Comp. Methods
- Initial Conditions

Time

Spatial Resolution

Physics

“Degrees of Freedom”

Protostellar Disk Rotation

Lifetime of MC

MC Dimensions

“Degrees of Freedom”
What is your question?

Star Clusters?
Turbulence in MC?
Accretion disks?
Binaries?

Physics
- Astrochemistry
- Radiation
  - heating
- Magnetic Fields
  - ohmic diss., AD, reconnection
- Gravity
- Turbulence

Time
-10 Myr - 10 Myr - 1 Myr - 0.1 Myr - 0.01 Myr

Spatial Resolution
-10 pc - 1 pc - 0.1 pc - 100 AU - 10 AU - 1 AU - 0.1 AU - 0.01 AU
Hydrodynamic Codes
HYDRODYNAMIC CODES

Grid:
Zeus, Athena

Adaptive Mesh Refinement (AMR):
ORION, FLASH, Enzo, AstroBEAR, TORUS

Smooth Particle Hydrodynamics (SPH):
Gadget, Gasoline, Bate-SPH

Moving Mesh:
AREPO
Tomida et al. 2015

Highlights

Result: OD and AD allow disk to form before 2nd core stage (protostar)

- Astrochemistry
- Radiation heating
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  - ohmic diss., AD, reconnection
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Highlights

Result: Magnetic fields lower SF efficiency by ~x2 and increase clustering

Myers et. al. 2015 (Berkeley Group)
Highlights

Result: IMF is invariant with metallicity from 0.01-3x solar.

Bate 2014

Physics

- Astrochemistry
- Radiation
  - heating
- Magnetic Fields
  - ohmic diss., AD, reconnection

Gravity
Turbulence
Highlights

Smith et al. 2014 (AREPO)

Result: Filaments have power-law profile ($p \sim 2.2$), no characteristic width
Metrics of Comparison

IMF
Multiplicity
SF Efficiency
Gas Properties

Success?!
Stellar Initial Mass Function

Radiation (gas heating/cooling) seems to be important.

Too Many Brown Dwarfs! (M < 0.1 Msun)

Offner et al. 2014, PPVI
Metallicity has minimal statistical impact. (see also Bate 2014)
**Stellar Initial Mass Function**

Impact of **Bfields** on the IMF is unclear or counterintuitive. 
(Li et al. 2010, Houck et al. 2012, Chen & Ostriker 2014, Myers et al. 2014)

<table>
<thead>
<tr>
<th>Model</th>
<th>IMF Exponent $\Gamma$</th>
<th>Characteristic Mass $M_{ch}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD</td>
<td>$-1.2$</td>
<td>$5.0 M_\odot$</td>
</tr>
<tr>
<td>MHD</td>
<td>$-1.4$</td>
<td>$1.3 M_\odot$</td>
</tr>
<tr>
<td>WIND</td>
<td>$-1.0$</td>
<td>$0.5 M_\odot$</td>
</tr>
</tbody>
</table>

Our results show that the core mass and size are relatively independent of both the ambipolar diffusion and the upstream magnetic obliquity (Figure 9). Hydrodynamic and ideal MHD models also have very similar core masses and sizes. The core mass $M_{core}$ is relatively independent of the magnetic field strength.

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Increasing BField
Impact of Bfields on the IMF is unclear or counterintuitive. (Li et al. 2010, Houck et al. 2012, Chen & Ostriker 2014, Myers et al. 2014)

No observational evidence for variation

... Bfield is self-regulating? Need non-ideal MHD?
Multiplicity
Simulations can reproduce observed field multiplicity.
Simulations can reproduce observed field multiplicity

A promising future diagnostic?
Outflow and Protostar Evolution

- Stage 0 Defn: $M^* < M_{\text{env}}$
- Sim. Stage 0 ~ 0.1 Myr
- Obs. Class 0 ~ 0.1 Myr (Enoch et al. 08)

Outflows reduce the Star-to-Core efficiency by 30-40% (Hansen et al. 2012, Machida & Hosokawa 2013, Offner & Arce 2014, Myers et al. 2014)

CMF to IMF ~ 30%
Gas Properties: Synthetic Observations

Synthetic Observation (noun): a quantitative model for the emission produced by a simulation and detected assuming the simulation is a real astronomical object at some point in the sky.

Statistic

Photons: $T_A(K)$, $\Delta v$, mJy

Abundances, Dust & Temperatures

Radiative Transfer

"Observe"
Ex. Molecular Cloud Structure

**SCF**

Gaches et al. 2015
see also Bertram et al. 2014 (PCA), Burkhart et al. 2013 (PS)?
Ex. FILAMENTS

Enzo → Dust Model → Juvela RT → Beam + Noise

Filament Profile

- Actual
- 93 pc
  .371 pc

Plummer Fits

Dust Emission
Juvela et al. 2012
(see also Smith et al. 2014)
Frontiers

Towards completeness
Top-down initial conditions
Brute Force

Time
Spatial Resolution

Physics
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1 yr
0.1 Myr
1 Myr
10 Myr
-10 pc
-1 pc
-0.1 pc
-100 AU
-10 AU
-1 AU
-0.1 AU
-0.01 AU
Conclusions

★ Star formation simulations are messy (even for low-mass stars)!
★ There are always tradeoffs in terms of time, resolution and physics ... but we’re making progress towards reality!
★ Simulations have now solved problems created by simulations: magnetic breaking catastrophe, over-production of BDs, too-high SF efficiencies!
★ Simulations are able to reproduce a largely invariant IMF with time and metallicity.
★ Simulations can reproduce field star multiplicity (with large error bars)!
★ Synthetic observations are needed to confirm success!