Simulating the Formation And Early Evolution Of Star Clusters

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Cluster formation

mass segregation

assembly/virialization

relaxation/collisional dynamics

stellar evolution

binary dynamics/evolution

stellar collisions

"Kitchen Sink" cluster dynamics

radiative processes

winds

star formation

Interstellar gas dynamics

gas dynamics/cloud collapse

Large scale galactic gas dynamics

cluster formation 1 Myr 10 Myr 100 Myr 1 Gyr
Overview of Our Questions

- Which formation channels dominate in realistic molecular cloud environments (more monolithic or more hierarchical)?
- How effective is realistic feedback on ejecting gas from the stellar population? How effective is this ejection at cluster disruption?
- What are the effects of a realistic natal gas environment (whether simply embedded or being ejected) on the evolution of cluster properties such as mass segregation or fractal dimension?
- Many others can be explored (effects of primordial binaries, dynamical binaries, brown dwarf dynamics, feedback leakage, ionizing photon escape fraction, feedback effects on ISM and B fields, IMF choice on SFR, etc).
Gravity Bridge (Fujii+2007)

- Couples Flash MHD (Fryxel+2000) to N-body codes such as ph4 (McMillan in prep) through gravity interactions of the stars and gas.
- Conserves both energy and momentum of the system.
<table>
<thead>
<tr>
<th>Flash (*AMUSE interface)</th>
<th>ph4 / Multiples / SeBa</th>
</tr>
</thead>
<tbody>
<tr>
<td>MHD (Fryxell+2000)</td>
<td>Atomic cooling (Hill+2012)</td>
</tr>
<tr>
<td>*Rad Trans (Bacynzski+2015)</td>
<td>*Mol cool (Neufield+1996)</td>
</tr>
<tr>
<td>*SN (Simpson+2016)</td>
<td>*Background FUV (Weingartner+2001)</td>
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<tr>
<td>*Star formation (Sormani+2017)</td>
<td>*Cosmic rays (Galli+2015)</td>
</tr>
<tr>
<td>*Ionization fraction solver</td>
<td>*Local gas extinction (Banerjee+2006)</td>
</tr>
<tr>
<td>Ionization heating (Bacynzksi+2015)</td>
<td>*Radiation momentum</td>
</tr>
<tr>
<td>*FUV local stellar heating (Weingartner+2001)</td>
<td>*EUV on dust (Draine 2011)</td>
</tr>
</tbody>
</table>

* code I either fully developed or contributed to development

In development: Fully implemented

Implemented, needs testing:
| Run       | $M$  | $r$ (pc) | $n_0$ | $\alpha$ | $|B|\, (\mu G)$ |
|-----------|------|----------|-------|----------|-----------------|
| RunM3V07A | $10^3$ | 5        | $10^3$ | 0.7      | 3.0             |
| RunM4V07A | $10^4$ | 10       | 500   | 0.7      | 3.0             |
| RunM5V07A | $10^5$ | 50       | 100   | 0.7      | 3.0             |
| RunM3V04A | $10^3$ | 5        | $10^3$ | 0.4      | 3.0             |
| RunM4V04A | $10^4$ | 10       | 500   | 0.4      | 3.0             |
| RunM5V04A | $10^5$ | 50       | 100   | 0.4      | 3.0             |
| RunM3V02A | $10^3$ | 5        | $10^3$ | 0.2      | 3.0             |
| RunM4V02A | $10^4$ | 10       | 500   | 0.2      | 3.0             |
| RunM5V02A | $10^5$ | 50       | 100   | 0.2      | 3.0             |
*Input* is a Weidner+2013 IGIMF or Kroupa+2001 IMF (choice). Note that for star formation resolved at 1 solar mass requires resolution at 1 AU.

Number of stars in each mass bin is calculated from a Poisson distribution as in Sormani+2017 (developed here independently).

A list of candidate stars is pulled for each sink particle.

Only if the sink can collect enough mass can the star form.

This means feedback can halt star formation.

Input IMF but **output SFR and SFE**.
The pinching instability: polarization “hour-glass” morphology in ONC

Pattle et al. (2017), arXiv:1707.05269
Magnetic fields are important for proper filament formation and by extension proper star formation. ($10^4$ run shown)
Note the SFE here is purely dynamically driven.
Mass in stellar half mass radius

Stellar half mass radii.
Gas and Stellar Density within 1 pc of Cluster

- \( \Sigma_* \)
- \( \Sigma_g \)

\( \Sigma \) enclosed in shell (\( M_\odot \text{ pc}^{-2} \))

Radius (pc)
33 solar masses
$10^4$ solar mass initial cloud
Winds + UV + FUV + rad pressure
No mass loading
What’s Cooking…

Note the inefficiency of the stellar feedback on the dense gas.

\[ \Gamma \sim n \text{ while } \Lambda \sim n^2 \]
Simulating individual clouds

Ibáñez-Mejía + 16b
Final thoughts

- Forming stars “the right way” is quite complicated.
- Feedback is often less effective than you might suspect.
- Feedback is a good place to attempt to test stochastic IMF vs. IGIMF (see Andrews+2013, 2014 and Guo+2016 for observational tests).

Next steps

- More analysis (track subcluster structure in merged clusters, fractal dim, energetics of gas and stars, etc).
- Write papers (Methods to be submitted soon, 1st science paper starting up).
- Get awesome post doc position (applying this fall, will work for bar tab).
Questions?
Weaver solutions
$\log(t/\text{yr})$

17 Orbits

$10^3 \text{AU}$

Energy Error in the Outermost Orbit for 100 kicks

$\log(\Delta E/E)$

$10^3 \text{AU}$

Log (t/yr)
Momentum Conservation of Gravity Bridge

- **gas**
- **sinks**
- **gas + sinks**

**Graph 1: X Momentum (g cm/s)**
- Y-axis: X Momentum (g cm/s)
- X-axis: log(t) (yr)
- Colors: Green (gas), Blue (sinks), Black (gas + sinks)

**Graph 2: Abs X Momentum Error**
- Y-axis: Abs X Momentum Error
- X-axis: log(t) (yr)
- Color: Black (gas + sinks)
Numerical Methods for Stellar Feedback

- Implementation of the FERVENT ray tracing method for long characteristics (Baczynski et al 2015) coupled to the particles in Flash with a new ionization solver.
- Supernova kinetic and thermal energy injection using the method of Simpson et al (2015). This method adapts the kinetic energy injection fraction on the fly to the grid resolution.
- Winds kinetic energy injection modelled on the above SN method which conserves both momentum and energy of the wind.
\( \Delta x = 1.0 \, \text{pc} \)

Energy (ergs)

Log10 Energy (ergs)

\( \log_{10} \) Time (Myr)

Energy for \( \Delta x \approx 0.8 \, \text{pc} \), \( n=49.0 \), kin E frac=0.2274

$\Delta x = 0.12$ pc

$t = 0.0$ Myr

Ibáñez-Mejía + 16b
# energy into the grid

if (with_sn):
    if (do_sn once):
        sn = True
        inj_x = -6.8130232380422451e+17 | units.cm
        inj_y = -2.9269741758314e+18 | units.cm
        inj_z = -5.804824289989956e+18 | units.cm
    tot_e = 1e51 | units.erg
    fracKin = -1.0 # 0.2273/4 # 1.0
    inj_mass = (25.91599633) | units.g
    if (sn):
        #hydro.particles_sort()
        dt = hydro.energy_injection(tot_e, fracKin, inj_mass, inj_x, inj_y, inj_z)
        print "Timestep after SN is ", dt
        t = t_0ld + dt
        print "Now evolving until t =", t
        do_sn once = False
        hydro.io_out('p1tpart')
    else:
        #for part in range(num_particles):
            #print "Stellar type =", stars.stellar_type[part]
            #if (13 <= stars.stellar_type[part].value_in(units.stellar_type) <= 15):
                #print "Going supernova at", stars.x[part], stars.y[part], stars.z[part]
                #inj_x = stars.x[part]
                #inj_y = stars.y[part]
                #inj_z = stars.z[part]
                #tot_e = 1e51 | units.erg
Weak scaling of the code for ~ 200 grids per processor
Physical Assumptions for RT Method

- Only the ionization of hydrogen is tracked, although radiation momentum pressure from photons is included.
- Dust pressure is not currently implemented, but is planned.
- IR pressure is ignored as we assume IR escapes immediately (single scatter approximation).
- Currently we use only one radiation bin (for the average ionizing photon energy). More could be used, but at increased cost (of extra rays).

<table>
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<tr>
<th>PE on dust</th>
<th>H2 dissociation</th>
<th>H ionization</th>
</tr>
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<tbody>
<tr>
<td>&lt;5.6 - 11.2 eV&gt;</td>
<td>&lt;11.2 - 13.6 eV&gt;</td>
<td>&lt;13.6+&gt;</td>
</tr>
</tbody>
</table>
Science!

Hierarchical Cluster Formation

Initial Conditions

$10^3 - 10^6$ solar masses

Formed from SN driven turbulence (which is still ongoing during our formation).

Magnetic fields present
Science!

Feedback triggered star formation.
SNR44
18h 56m 48
+01 18’ 45”

ESA/PACS/SPIRE/Quang Nguyen Luong & Frederique Motte, HOBYS Key Program consortium (far-infrared).

ESA/XMM-Newton(x-ray).