Halo Globular Cluster Formation within a Cosmological Context


Astronomy Department, University of Florida

10 April 2010, Gainesville: *Stars to Galaxies*
From cosmological ICs, the formation of the first stars are being simulated

- Start with cosmological initial conditions
- Go from $\sim 1$ Mpc comoving to $\sim$ AU
- Capture fragmentation of primordial gas
- Model feedback, metal enrichment, second generation
- Expect pop III masses $\sim 10$-$100 M_\odot$ to a factor up to a few

Image from Turk et al. 2009. For discussion of these topics see, e.g., Bromm (2001), Glover (2005), O’Shea & Norman (2007), McKee & Tan (2008), Bromm et al. (2009), Jappsen et al. (2009), Wise & Abel (2009), Greif et al. (2010)
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What’s the right fossil?
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- **Halo and Disk GCs**
  - Typical mass $\sim 2 \times 10^5 M_\odot$
  - Typical half-light $r \sim$ few pc
    - Disk clusters (red) have thick-disk-like kinematics
    - Halo clusters (blue) are on radial orbits, similar to halo stars

Figure 1

$V-I$ color histogram of globular clusters in the Virgo giant elliptical M87, showing clear bimodality (Larsen et al. 2001; figure from data courtesy of S. Larsen).

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HGCs are old, but old enough?

d e Angeli et al. (2005); Sarajedini et al. (2007)
Radial biasing mass constraints

Where do high-$\sigma$ peaks ($\nu_\sigma(M,z)$) end up? 

Diemand et al. 2005, Moore et al. 2006
Radial biasing

Moore et al. (2006)
Do they share a history with halo stars?

Halo stars have: e.g., Helmi et al. (2008)

- similar metallicity distribution
- similar ages
- similar biasing

\[ \text{Mass} \sim 2-8 \times 10^8 \, \text{M}_\odot \] (taking into account destruction, e.g., see Gnedin & Ostriker 1997)

Mass for HGC formation requires \( 5 \times 10^8 \, \text{M}_\odot \), not just \( \text{few} \times 10^7 \, \text{M}_\odot \)

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Collapsed mass and biasing
Using Press-Schechter theory with Sheth-Tormen formalism
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Now for an example
I Leave You With A Metallicity Example

Top: Gas density with stars and metallicity distribution for a high feedback case. The snapshot is about 20 kpc proper across.
I Leave You With A Metallicity Example

Histograms of the mass within a given metallicity bin for each simulation. Left panel, little feedback. Right panel, a lot of feedback. In these examples, only supernovae feedback faeries. The binning for \([\text{Fe/H}] < -6\) is used for a different diagnostic, and does not represent pop II stars.
Summary

- A large fraction of halo stars could be formed with HGCs.  
- Enough mass was collapsed in high-$\sigma$ peaks to produce the halo and HGCs before $z \sim 10$.  
- Small age dispersion of HGCs is naturally explained if formed at $z > 10$.  
- Assuming $30 \text{ Mpc}^3$ comoving volume, $5 \times 10^8 \text{ M}_\odot$, and 200 Myr, $\sim 0.08 \text{ M}_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}$ as an upper limit  
- Simulation of a 1 Mpc comoving box must resolve HGC formation  
  - If not, something is wrong with the model and/or the cosmology  
- Constrain the feedback faeries  
  - Metal distributions  
  - Global SFE (should be $\sim 10\%$)
Appendix

- RAMSES
- Non-equilibrium chemistry: e, HI, HII, Hel, Hell, HelIII, H^-, H_2, H_2^+
- Used a population III star formation algorithm
  - Sample a Salpeter IMF, with high-mass, low-end cutoff
  - Switch to population II star formation if \( Z > 5 \times 10^{-7} Z_\odot \) (so they can form if they can)
- \( 256^3 \) in ROI \( \rightarrow 1000 \, M_\odot \) DM particle mass
- Box size about 820 kpc comoving
Appendix: Chemistry check
Appendix: Subgrid fun (nonsense)

<table>
<thead>
<tr>
<th>Mass Range $M_{\odot}$</th>
<th>Outcome</th>
<th>$t_{SN}$ (Myr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt; 8$</td>
<td>$M_{LL}$</td>
<td>$-$</td>
</tr>
<tr>
<td>$8 &lt; M &lt; 25$</td>
<td>$M_{LL}$, $M_{ejecta}$</td>
<td>$10$</td>
</tr>
<tr>
<td>$25 &lt; M &lt; 35$</td>
<td>$M_{BH}$, $M_{ejecta}$</td>
<td>$10$</td>
</tr>
<tr>
<td>$35 &lt; M &lt; 140$</td>
<td>$M_{BH}$</td>
<td>$-$</td>
</tr>
<tr>
<td>$140 &lt; M &lt; 260$</td>
<td>$M_{ejecta}$</td>
<td>$3$</td>
</tr>
<tr>
<td>$260 &lt; M$</td>
<td>$M_{BH}$</td>
<td>$-$</td>
</tr>
</tbody>
</table>

Table: The mass in long-lived stars and remnants, $M_{LL}$, black holes, $M_{BH}$, and ejecta mass $M_{ejecta}$. The remnant mass, either black hole or neutron star, is determined by $M_{R/BH} = \text{MAX}(M_{\text{star}} 0.1^{13.5M_{\odot}/M_{\text{star}}}, 1.35M_{\odot})$, which is based on the results of Timmes et al. (1996). The ejecta mass is the difference between star’s mass and its remnant. In the case of a pair-instability supernova ($140 < M < 260M_{\odot}$), the ejecta mass is set to the star’s mass. The third column, $t_{SN}$, is the supernova delay time.
Appendix: Comes with the following feedback fairies

- Only supernova feedback is included
- Population II star particles release 10% of the mass as ejecta, of which 1/10 is mass in metals
- Typical star particle is about 200 $M_\odot$. Can be more
- Star formation is regulated by feedback. High local efficiency leads to more stars at once, which leads to bigger collective boom
Appendix: An illustrative example

360 pc Density

90 pc Stars

Temperature

[Graphs showing density and temperature distributions, as well as a histogram of metallicity (Fe/H)]