Figure 2: The age of expansion vs the age of globular clusters, as a function of the formation redshift $z_f$ (eq. 3). Shaded box contains the current values of $t_{fH}$ and $t_{fH}$ within the observational errors. In a flat Universe with $\Omega_m = 1 - \Omega_m = 0.7$, the age of expansion in $t_{fH} = \frac{3}{2}H_0^{-1} \Omega_{\Lambda}^{-1/2} \ln[(1 + \Omega_{\Lambda}^{1/2})(1 - 
abla_{\Lambda}^{-1/2})]$.

Tom Quinn et al.

2006p. 0208034
but GCs (probably) can't all form in dwarf galaxies:

- correlation between $Z_{GC}$ and $L_{host}$

- $S_N$ higher in early type galaxies (e.g. Harris 1991, McLaughlin 1999)


FIG. 10.— Mean color (metallicity) of globular cluster systems, plotted against galaxy magnitude (v. mag). The dashed line shows the "iso-age" relation between galaxy mass and globular cluster metallicity shown in Figure 1 for composite protogalactic fragments, i.e., globular clusters formed in galactic discs and the bulge components of giant galaxies (filled rectangles). The filled square and circle indicate observed colors for the metal-poor peak and metal-rich peak, respectively, in the 18 galaxies classified as unimodal by Sandage & Whitmore (2002). Open squares and circles indicate the median values of those components based on 100 simulations of the globular cluster metallicity distribution function (Peletier et al. 1980) presented in Table 1. The filled and open triangles show the observed and simulated values of globular clusters belonging to the 12 galaxies classified by Sandage & Whitmore (2001) as unimodal. The structure in the lower right corner shows the $M_B$ scatter around normal solar values. For each galaxy with a bimodal metallicity distribution, a thin arrow connects the original position of the most massive protogalactic fragment (open stars) to the reassigned position of the metal-rich peak.
2 mass scales

\[ \text{M}_{\text{sub}} \gg \text{M}_{\star} \]

Pre-requisites for fragmentation:

\[ \text{Local} < \text{E}_{\text{sub}} \]

Rees & Ostriker 1977

AND

Non-linear density structure at onset of cooling

Larson 1978

Klessen et al. 1998

Both et al. 2001

\[ \text{Compatible with pressure supported progenitor?} \]

Like local star formation in GMCs

Melus set by dynamic potentials...
- mass function of young globular clusters in mergers has the same slope as mass functions of GMCs. [Eg. Elmegreen & Elmegreen 1997]

- mass function of MW GCs shaped by survival against disruption, but

- need initial mass function of MW GCs to steeper at $M_{\text{clus}} = 10^6 - 10^7 M_\odot$ (e.g. Fall & Zhang 2001).

- proto-GCs versus GMCs
  - masses similar
  - $r_2 = 3$ pc
  - $r_2 = 20$ pc
  - $E = M_\odot / M_{\text{clus}} \geq 25\%$
  - $E = 0.2\%$
  - (to be bound)

- does efficient feedback in GMCs inflate them? X

- does compactness of proto-GCs $ightarrow$ short time? maybe
  - due to inefficient feedback?

- does compactness of proto GCs result from high P environment?
GCs don't have significant DM halos.

or significant DM within optical radius.

(Priar et al. 1989).

GCs of Pop. III ($Z < 10^{-2} Z_0$) but not self-enriched.

branch width of Giant
Evolution of mass function of GCs
- $z = 0, 1.5, 3, 4 < 12$ Gyr
- = observed mass function in MW

A successful GC formation scenario which are a little populated, composed of chemically homogeneous, $Z \approx 10^{-2} Z_o$

from Fall & Zhang 2001
astro-ph 0109295.
GC Formation in Cosmological Simulations


Vol. 556

- $M_{DM} = 5 \times 10^5 M_\odot$
- $M_{gas} = 10^8 M_\odot$
- Identify bound gas clouds as Super Giant Molecular Clouds (SGMCs) in which GCs may form
- Resolution limits: $r_{res} \approx 1 \text{ kpc}$
  $M = D_{res} \times 10^5 M_\odot$

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SUPERGIANT STAR-FORMING CLOUDS

- Mass spectrum of combined dark matter clumps for all seven runs shown at nine redshifts. The solid lines show power-law fits, as described in the previous figure caption. The dotted and dashed lines are fits of the Press-Schechter multiplicity function of eq. (1) with $\alpha = 1$ and $\alpha = 0$, respectively.

"mass spectrum of DM clumps"

- Like GCs!

("See also Con 2001, Odenkirchen et al. 2001, Bowman Clarke 2001")

If this is relevant to GC formation, then similarity with GMC mass spectrum is fortuitous.
GC formation in low mass haloes?

Cen (2001) envisaged gas 'sitting idly' in low mass haloes

...ionization $\rightarrow$ shock compression

collapse

... but would it sit idly?

(from Brown et al. 2002)
\[ z = 15 \]

\[ M_{\text{DM}} = 2 \times 10^6 M_\odot, \quad Z = 10^{-2} Z_\odot \]

Clump masses: \( 4 \times 10^4 M_\odot, 5 \times 10^4 M_\odot, 2 \times 10^3 M_\odot, \]
\( 3 \times 10^5 M_\odot, 1.3 \times 10^6 M_\odot, 2.2 \times 10^5 M_\odot \)

- are these GCs, if not, what are they?
How does model perform?

- fragmentation? can't say yet
- sizes? $r \lesssim 10$ pc, $t_{\text{mp}} \lesssim 10^6$ years.
- mass distribution?
  power law from DM clustering statistics
  $M_{\text{min}} = M_{\text{res}}$
  $M_{\text{max}}$ = good fraction of total baryon mass
  (most massive clump is not GC-like)
  *nucleus of dwarf*)

- association with DM? halos crowded ✓

EPS calc. of mass spectrum of haloes which at $z=15$ will have merged into a dwarf galaxy mass
$M = 2 \times 10^9 M_{\odot}$
Unsolved Problems I

What sets $M_{\text{max}}$?

- invoke change in DM power spectrum?
  
  $P(k) \propto k^n$, mass variance $= \int_0^\infty P(k) k^2 \, dk$
  
  $M = L^2 \Rightarrow$ variance $< M^{-\left(\frac{n+3}{2}\right)}$

  $n$ close to 3, variance flat

  small scale regime $\Rightarrow$ efficient erasure of DM substructure

- stop process at $z = 7$
  
  (re-ionisation prevents gas collapsing in small halos)

- not "globular like" at lower $z$
  
  (longer $t_{\text{ff}} \Rightarrow$ efficient feedback).