Globular Cluster Formation at High Density: A model for Elemental Enrichment with Fast Recycling of Massive-Star Debris

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Wünsch, R.; Palous, J.; Tenorio-Tagle, G.; Ehlerová, S. 2017, Formation of **Secondary Stellar Generations** in Massive Young Star Clusters from Rapidly Cooling Shocked Stellar Winds, ApJ, 835, 60

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Thanks Guillermo, for the inspiration …

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Palous, Jan; Wünsch, Richard; Tenorio-Tagle, Guillermo; Silich, Sergio 2009, The astrophysical consequences of the **bimodal hydrodynamic solution** of the super star cluster winds, Ap&SS, 324, 195

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The Story

1. Every old MW globular cluster has a mixture of stellar populations with O/Na ranging from high for the first generation (G1) to low for the second generation (G2), with a comparable number of stars in each type.

2. Interpretation:
    1. the original gas had high O/Na but nuclear reactions ($^{22}Ne \rightarrow {}^{23}Na$) with simultaneous O destruction at $T=2x10^7K$ lowered O/Na inside those G1 stars
    2. Mg and Al anticorrelate too, probably from the Mg/Al cycle (Mg → Al) at $T>7x10^7K$.
    3. The p-processed elements in G1 **came out of those stars**, mixed about 1:1 with more original gas, and **got into new stars** to various degrees, which are G2

The Theoretical Problem:

1. Unknown whether the p-process elements formed in main sequence stars or AGB stars
    1. Often, (C+N+O)/H is constant, consistent with the CNO cycle in MS stars
    2. If MS stars, how did the p-process gas get out of them?
       (the enrichment happened in the nuclear burning zone)
2. There is no Fe enrichment in G2, and therefore no supernova debris, so G2 formed *either*:
    1. **before the SN** (for the MS enrichment scenario)
        1. Cottrell & Da Costa '81, rapidly spinning massive stars: Prantzos & Charbonnel '06, Decressin et al. 2007
        2. In binary massive stars with Roche lobe overflow (de Mink et al. 2009)
    2. or, **after the SN** (for the AGB star enrichment scenario)
        1. Ventura & D'Antona '05, DErcole +08, Yong +14; Marino +15; Renzini +15, D'Antona +16; Simpson +17

- possibly via protostellar disk accretion (Bastian +13; Salaris & Cassisi '14; Cassisi & Salaris '14)
- or possibly involving supermassive stars (Denissenkov & Hartwick '14; Denissenkov +15)
- via GC merging in dwarf galaxy hosts (Bekki & Tsujimoto '16)
- via AGB wind recollection in the pressurized cavity around the GC (D'Ercole +16)

4. WR stars might deliver p-process elements, but the time between the WR phase and the SN phase seems too short to form all of G2 then.

The Observational Problem:

1. Difficult to study SF and abundances in massive clusters younger than 3 Myr (before SN)

2. Searches for SF in 100 Myr massive clusters (the AGB scenario) have failed
    1. Bastian +13; Cabrera-Ziri +14, 16 (but see Li +16)

3. Searches for gas in 100 Myr massive clusters have also failed
    1. Bastian & Strader 2014

The Observational Problem, continued:

4. The p-processed debris itself is only a **small fraction** of the G1 mass, so the original G1 mass had to be the inverse of this fraction times about half the G2 mass (the contaminated fraction)

$\sim$20x for massive star model (Decressin +07), and >10x for AGB (D'Ercole +08; Tenorio-Tagle +16)

- often a peculiar IMF for G2 is assumed: lacking intermediate and high mass stars)

5. All of these extra G1 stars had to **escape the cluster** into the GC-galaxy's halo,
   - which is OK for the Milky Way (Prantzos & Charbonnel '06; Martell +11)
   - but such G1 halos are not seen in Fornax (Larsen +12, 14) or WLM (Elmegreen +12)

6. In the massive-star scenario, gas removal before SNe is difficult, resulting in a **high SF efficiency** and tight-binding of the G1 stars, preventing escape (Krause et al. 2016)

A new solution (Elmegreen 2017):

1. Consider that all old GCs formed in the **early Universe** when the SFR and gas surface densities were 10x higher than today
    1. 10x Σ_{gas} → 100x the pressure → old GCs formed at **100x the density** of SF today

2. As a result:
    1. the ratio of the gas consumption time to the SN time (~3 Myr) is small, ~10%
       → **lots of time to recycle** stellar debris from G1 to G2 without SN contamination
    2. the interaction between stars in the cluster is strong
       → **stellar collisions are frequent**
        1. sometimes forming supermassive stars – Ebisuzaki +01; Bally & Zinnecker '05
        2. mixing rotationally extruded stellar disks – Prantzos & Charbonnel '06

       → **massive star binaries collide** with single stars, puff up, and eject ~10% of their envelope mass (Freqeau +04, Gaburov +10, Umbreit +08)
       → low mass stars are continuously **ejected** by stellar interactions and the time-changing potential of debris-driven explosions (~SN energy – Gaburov +10)

Basic model:

1. Cloud core M ~ 4×10^6 M_O inside R=3 pc, and surrounded by a low-density envelope up to 10^7 M_O
   1. Then the final GC has a mass of ~2×10^5 M_O: 90% loss from stellar escape (shown here) and 50% loss from 10 Gyr of evaporation (McLaughlin & Fall ‘08)
   2. Then the core free fall time is 0.03 Myr (density = 10^6 atoms/cm^3)
   3. The core potential is deep, 80 km/s, so gas ejection by MS winds is difficult and SF is efficient
      1. subsequent cluster expansion (Gieles & Renaud ‘16) will decrease σ to today’s value
      2. stellar ejection at σ will be high-speed, possibly causing the ejected stars to leave the galaxy, and thereby solving the Fornax and WLM halo population problem
      3. the SF efficiency/ free-fall time should be high: 10% (10x higher than today)
      4. so the consumption time is 0.3 Myr ~ 10% of the supernova time
   4. This core formation rate is high, 130 M_O/yr, but consistent with σ^3/G for σ~80 km/s for the high σ in young galaxies (Förster Schreiber +09)
   5. The SF rate in the core will be so high that HII/wind feedback will not be important
   6. The surface density of 10^5 M_O/pc^2 is close to the maximum (Hopkins +10; Walker +16)

→ such clouds and cores are **expected for high redshift galaxies**, and SF in them will be so rapid that **nearly everything is finished before the SN phase begins.**

Also assume:

1. A **normal IMF** for all generations (a Salpeter power law with a log-normal turn over at low mass; Paresce & De Marchi ’00)

2. $M > 20\ M_O$ stars make p-process elements (Decressin +07) and mix them into their stellar envelopes, which consist of all of the stellar mass outside of the He core (Prantzos & Charbonnel ‘06)

3. For $M_{upper} = 100\ M_O$, $f_{env} = 7.9\%$ (= fraction of stars with $M>20M_O$ [12.1%] and the average fraction of this stellar mass in the form of envelopes [65.1%].

4. For $M_{upper} = 300\ M_O$, $f_{env} = 9.3\%$ (16.4% of IMF $>20M_O$, and 56.8% of that in envelopes)

5. Also the fraction of the total stellar mass in long-lived, low-mass stars ($M< 0.8M_O$) is f_{LM} = 31.2% and 29.7%, respectively.

The basic equations:

Stellar mass increases from SF:

$$dM_{\rm star,LM}/dt = f_{\rm LM}\, M_{\rm gas}(t)/t_{\rm consume},$$

$$dM_{\rm star,IM}/dt = f_{\rm IM}\, M_{\rm gas}(t)/t_{\rm consume},$$

$$dM_{\rm star,HM}/dt = f_{\rm HM}\, M_{\rm gas}(t)/t_{\rm consume},$$

where for $M<0.8M_O$: $f_{LM} = 0.312$, $0.8M_O<M<20M_O$: $f_{IM} = 0.567$, and $M>20M_O$: $f_{HM} = 0.121$ for an IMF with a most massive star of $100M_O$, and $f_{LM} = 0.297$, $f_{IM} = 0.540$, and $f_{HM} = 0.164$ for $M_{max} = 300M_O$

However, the ejection of LM stars is important (not IM and HM stars), so keep track of that by revising the LM rate:

$$dM_{\rm star,LM}/dt = f_{\rm LM}\, M_{\rm gas}(t)/t_{\rm consume} - f_{\rm eject}\, M_{\rm star,LM}/t_{\rm consume}$$

The gas has to be separated between unprocessed ("1") and processed ("2"):

Unprocessed gas:

$$\dot{M}_{\mathrm{gas},1}(t) = \int_0^t \left(\frac{f_{\mathrm{debr}} \dot{M}_{\mathrm{star,HM}}(t')}{t_{\mathrm{evol}}} \right) (1 - f_{\mathrm{p}}(t')) \times \left[1 - \frac{t - t'}{t_{\mathrm{evol}}} \right] dt' + R_{\mathrm{acc}}(t) - (1 - f_{\mathrm{p}}(t)) \dot{M}_{\mathrm{star}}(t).$$

1st term: what returns in unprocessed stellar debris for the unprocessed parts of stars (1-f_p) formed at the previous time t' considering a linear buildup of processed material in the stellar envelopes over time (1-[t-t']/t_{evol}). … note that $f_p = M_{gas,2}/(M_{gas,1}+M_{gas,2})$

2nd term: Accretion of unprocessed gas from the cloud envelope

3rd term: what gets locked up into stars

The gas has to be separated between unprocessed ("1") and processed ("2"):

Processed gas:

$$\dot{M}_{\rm gas,2}(t) = \int_0^t \left(\frac{f_{\rm debr}\dot{M}_{\rm star,HM}(t')}{t_{\rm evol}}\right)(1-f_{\rm p}(t'))\left(\frac{t-t'}{t_{\rm evol}}\right)dt' + \int_0^t \left(\frac{f_{\rm debr}\dot{M}_{\rm star,HM}(t')}{t_{\rm evol}}\right)f_{\rm p}(t')dt' - f_{\rm p}(t)\dot{M}_{\rm star}(t).$$

1st term: what returns in processed stellar debris for the unprocessed parts of stars ($1-f_p$) formed at the previous time t' considering a linear buildup of processed material in the stellar envelopes over time ($[t-t']/t_{evol}$)

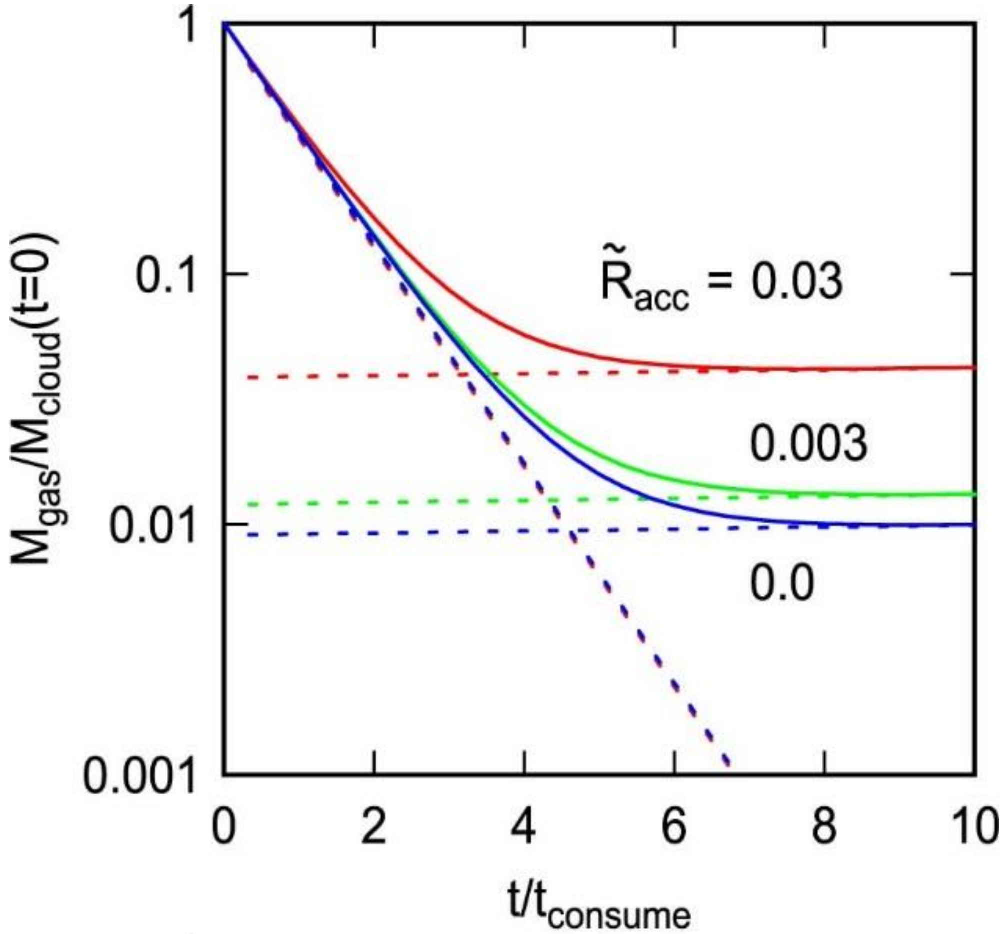
2nd term: what returns in stellar debris from the previously processed parts of stars (f_p)

3rd term: what gets locked up into stars

Results:

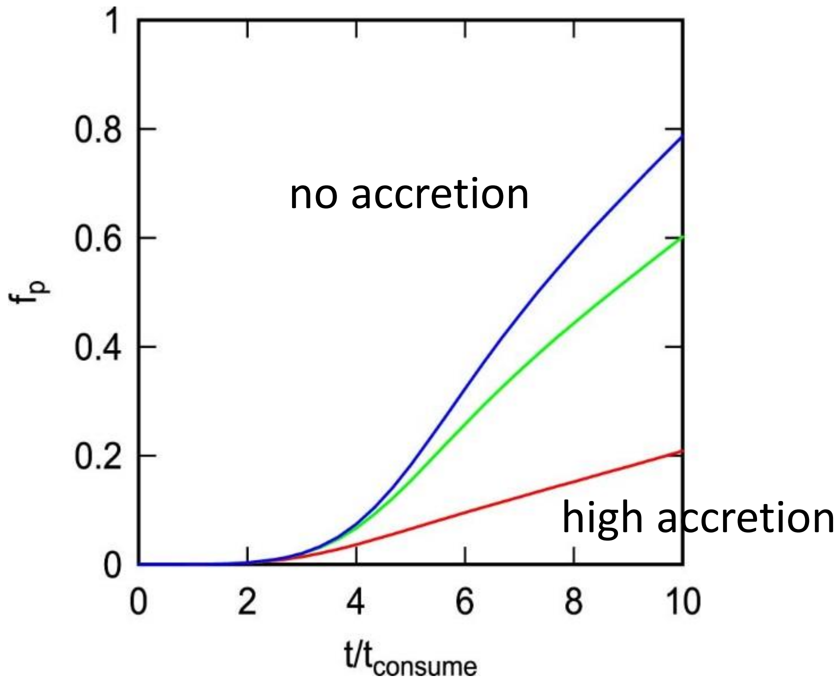
The total gas mass* in the core versus time* for 3 different accretion rates.

Dotted lines are asymptotes for analytical solutions**

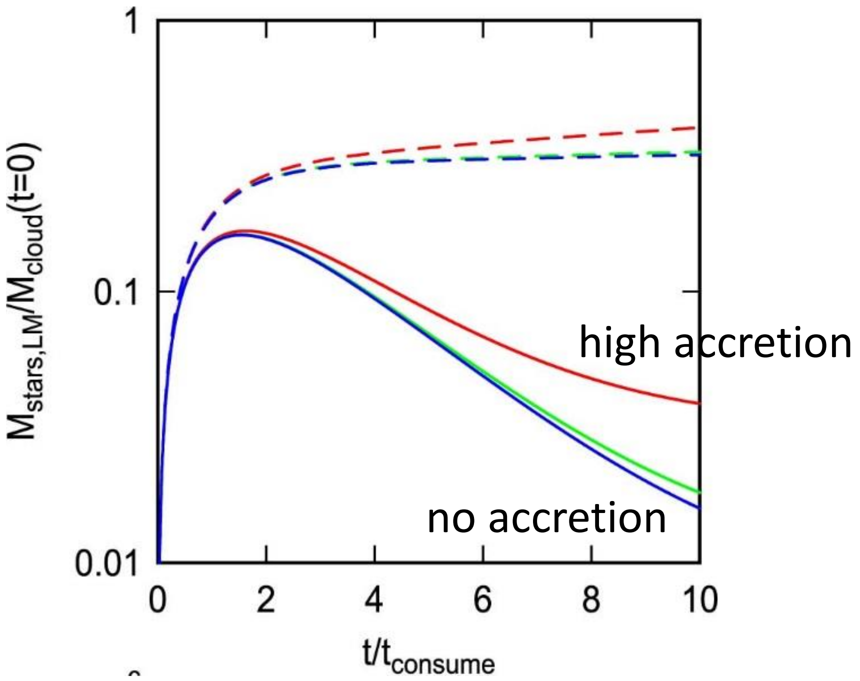


* Normalize quantities to the initial cloud core mass and the consumption time.
** Analytical solutions possible for total gas and stars
*** Assumed IMF goes to M_{max} = 300 M_O

Results:



Processed fraction versus time.



Relative mass of LM stars without (dashed) and with (solid) ejection, assuming f_{eject}=0.4

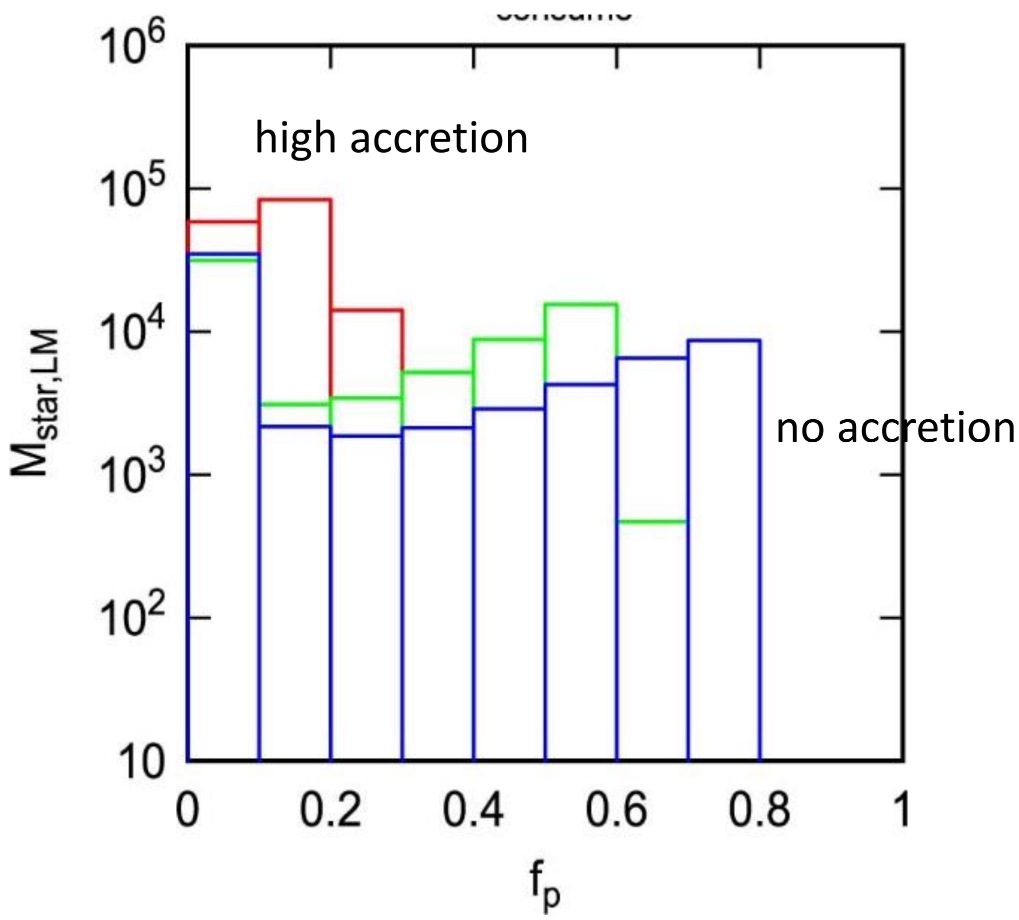
Distribution of processed fraction among LM stars after t_{evol} (when SF stops because SN begin).

Observations of Lithium suggest f_p can be up to 0.7 in some cases.

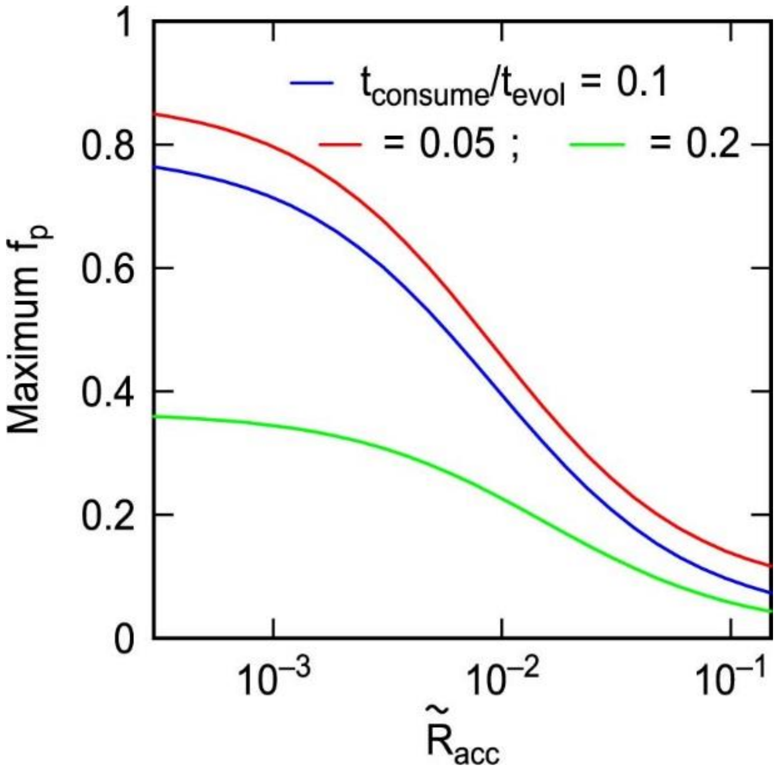
The G2 fraction is the ratio of all histograms to the right of the first, to the total:

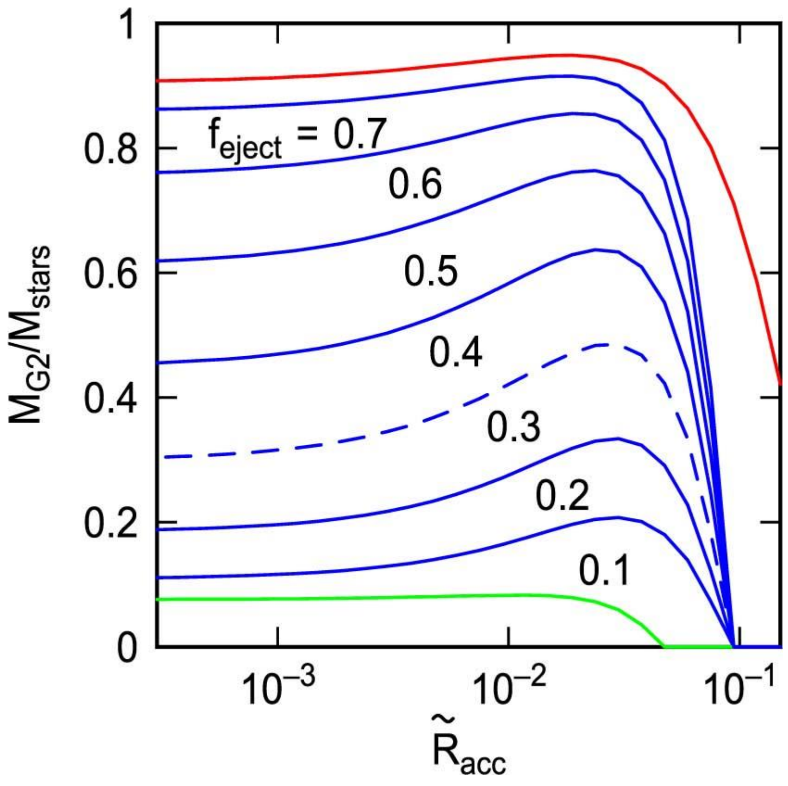
R_{acc} = 0.03 (red lines): 0.63
R_{acc} = 0.003 (green): 0.50
R_{acc} = 0 (blue): 0.43

… consistent with observations.



The effect of the ejection and accretion rates:

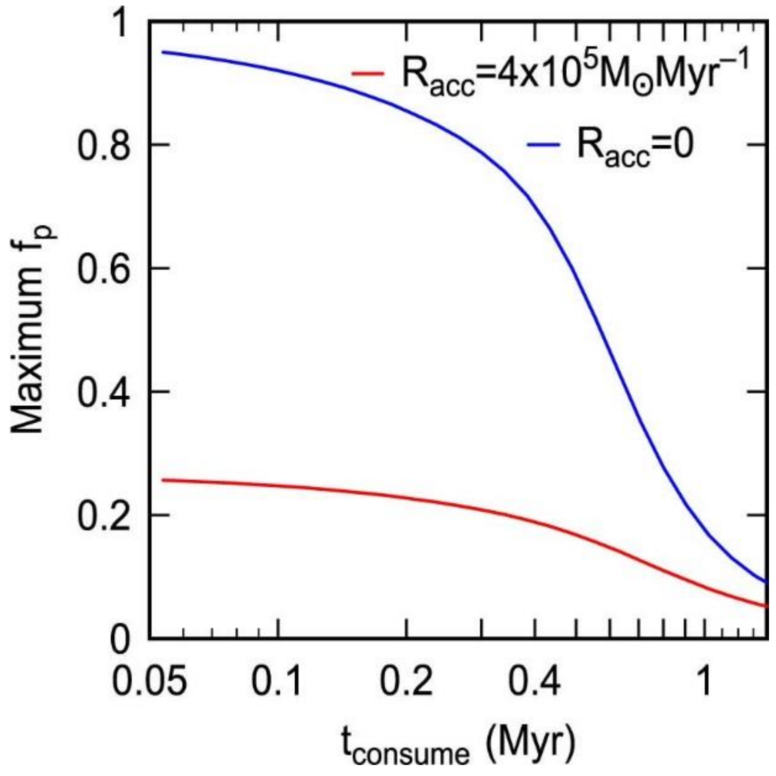




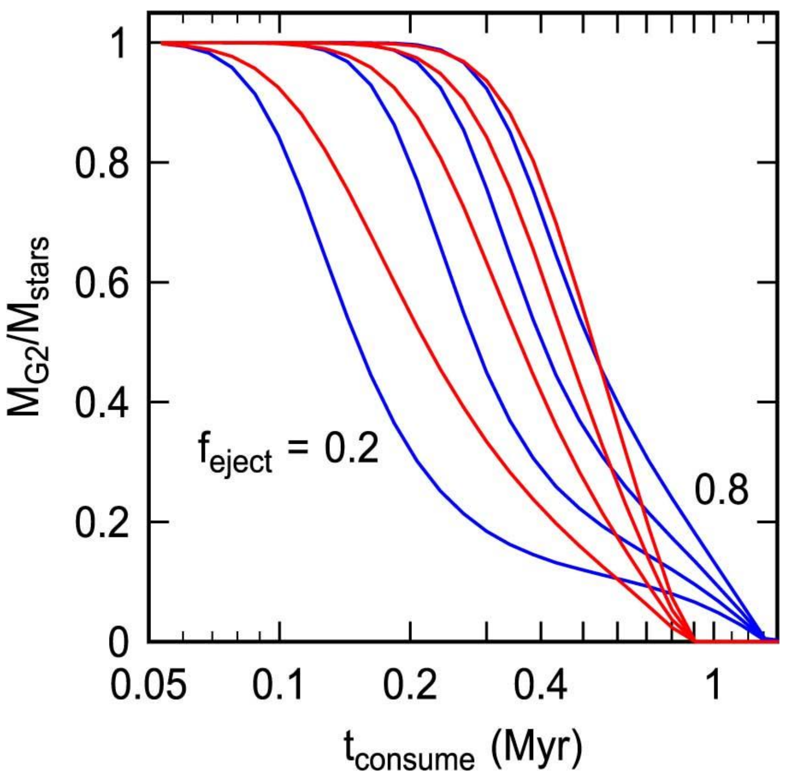
Slower accretion and faster SF (lower $t_{consume}$) lead to a higher processed fraction

Slower accretion and faster ejection (lower t_{dyn} and therefore $t_{consume}$) lead to a higher G2 fraction

The effect of the gas consumption time (= M_{gas}/SFR)



Faster SF (lower $t_{consume}$) leads to a higher processed fraction



Faster ejection (lower t_{dyn} and therefore $t_{consume}$) leads to a higher G2 fraction

Conclusions:

1. The maximum processed fraction of individual stars and the fraction of stars showing some processed material both increase with increasing cloud core density.

2. The old globular clusters should have had a higher initial density than today's young massive clusters because star formation was more active in all galaxies at high redshift (pressure increases with SFR).

> Thus old globular clusters are be expected to have larger p-process anomalies than young massive clusters (unless the YMCs form at similarly high densities).

3. To do: envelope dispersal rate for HM stars; cluster ejection rate for LM stars.