Studying High-Redshift Star Formation with the GMT

Evan Scannapieco
Arizona State School of Earth and Space Exploration
Two types of star formation not seen today:

I. Primordial star formation

II. Outflow induced star formation

What are these and how can we search for them with the GMT?
I Metal free stars: Cooling

\[ T_{\text{vir}} \geq 10^4 \text{ K} \]

Gas masses \( \simeq 10^7 M_\odot [(1+z)/10]^{-3/2} \)

Sutherland & Dopita (1993)
“Minihalos”

50 kpc box, \( T_{\text{vir}} < 10^4 \text{K} \)

\( T_{\text{vir}} \leq 10^4 \text{K at } z \sim 10 \)

Shapiro et al (2005)
Little bit of notation

Primordial $\Rightarrow Z=0$

Population III $\Rightarrow$
1. $Z = 0$
2. $Z < Z_{\text{crit}} = 10^{-4} Z_\odot$ (where IMF may change)
3. Cool via Molecular Hydrogen
“First Galaxies”

\[ T_{\text{vir}} > 10^4 \text{ K}, \text{ masses } \geq 10^8 \text{ M}_{\odot} \]

- **Oh & Haiman 2002**: Such large primordial halos with first cool by Lya into a disk, but would begin to form H\(_2\), thus a similar story may hold as in the smaller objects.
- **Going to assume that the same story holds for all primordial (Z < Z_{\text{crit}}) objects, regardless of mass.** (see also Wise & Abel 2008; Bromm & Yoshida 2010)
Method I: Search for Primordial Galaxies

Primordial, typical IMF  Primordial, VMS

\[ E_g = \frac{\text{Kinetic Energy}}{\text{Baryon Mass into Stars}} \]

\[ 10^9 \, M_{\text{sun}} \quad 10^8 \, M_{\text{sun}} \]

\[ 10^7 \, M_{\text{sun}} \quad 10^6 \, M_{\text{sun}} \]

\[ Z/10^{51} \, \text{erg} \sim 2, \quad \text{SNeII, SNe\gamma\gamma} \]
Chemical Feedback

ES & Barkana (2001)  
ES, Schneider, Ferrara (2003)
Observability

Lyman-Alpha Detection Probability

Primordial, typical IMF

Primordial, VMS

ES, Schneider, Ferrara (2003)
Very massive or not, $Z=0$ stars are hot

High EWs  HeII lines

ES, Schneider, Ferrara (2003)
Tumlinson, Shull, Venkatesan (2003),
See also Schaefer (2003), Oh, Haiman, & Rees (2001)
< 10% of one particle!

Tornatore, Ferrara, & Schneider (2007)

ES, Schneider, & Ferrara (2003)
BX418: $z=2.3$, young ($< 100$ Myr), low mass ($M_* \sim 10^9 M_\odot$), low metallicity ($Z \sim 1/6 Z_\odot$), and unreddened ($E(B-V) = 0.02$).

\textit{Erb et al. (2011)} C IV/C III] ratio, not suggestive of AGN
Pair-production SNe?
II: Outflow-induced star formation

- In a sample of 19 Ly-break z~3 starbursting galaxies, winds were found in all objects.
- Velocities ~200 km/s
- Lyα-nebular emmi. + metal absorption-nebular emission.
- SFR ~ 20 M☉/yr

- Ionizing photons get trapped behind outflows

Wind-Minihalo Interaction

$E_{\text{wind}}$ is $10^{56}$ ergs
NFW halo $\Rightarrow M=10^{6.5} M_{\text{sun}}$
$Z \sim 10^{-1.5} Z_{\text{sun}}$

Fiducial Interaction

\[ E = 10^{56} \text{ ergs} ; \quad M = 10^{6.5} M_{\text{sun}} ; \quad Z \sim 10^{-1.5} Z_{\text{sun}} \]

Free-fall time
Sound Xing time
Cooling time

Cooling by:
nonequilibrium H2, HD formation


\[
( H + e \rightarrow H^- + h\nu ; \quad H^- + H \rightarrow H_2 + e )
\]

\[
( H + H^+ \rightarrow H_2^{++} + h\nu ; \quad H_2^{++} + e \rightarrow H_2 + H^+) 
\]
FLASH3 (AMR) Simulations

- initially hydrostatic cluster, fully neutral, static gravity
- 1 kpc^2 x 2.0 kpc box  5 levels of refinement, 4 pc effective resolution,
- NFW halo \( M_{\text{tot}} = 3 \times 10^6 M_\odot \)
- 150 km/s 5 Myr shock
- Saguaro computer cluster (5280 core cluster at ASU)
- Chemistry and Cooling

Gray & ES (2010)
Chemistry

- 14 Species in 84 Reactions (Abel & Glover ‘08)
  - H, H⁺, H⁻, D, D⁺, D⁻, He, He⁺, He++, HD, HD⁺, H₂, H₂⁺, e⁻
  - No 3-body reactions
  - No reaction with D₂

- An implicit Runge-Kutta Method (4th order) is used to evolve the chemistry

- Sub-cycles over network
  - Run chemistry at smaller timescales while still running simulation at hydrodynamic timescale

Gray & ES (2010)
Test Results

--Fixed T and n
--Primordial Composition
--H and He initially (singly) ionized

\[ T = 100 \, \text{K} \]

- Blue: \( n = 0.01 \, \text{cm}^{-3} \)
- Red: \( n = 0.1 \, \text{cm}^{-3} \)
- Green: \( n = 1.0 \, \text{cm}^{-3} \)
- Yellow: \( n = 10.0 \, \text{cm}^{-3} \)
- Teal: \( n = 100.0 \, \text{cm}^{-3} \)

Gray & ES (2010)
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Gray & ES (2010)
Cooling and Heating

- Within each chemistry subcycle
  - Account for internal energy change due to Recombination/ionization
  - Implement radiative cooling. (at low T, H₂, HD are the major coolants).

Gray & ES (2010)
Log10 h2

$x$ (cm)

$1 \times 10^{21}$

$1 \times 10^{21}$

$-10$  $-8$  $-6$  $-4$  $-2$  $0$

$0$  $2 \times 10^{21}$  $4 \times 10^{21}$

time = 0.000 ps
number of blocks = 3593
AMR levels = 6
Log10 Temperature (K)

time = 8.839 Myr
number of blocks = 12265
AMR levels = 6
Log10 h2

x (cm)

1 x 10^21

1 x 10^21

-10 -8 -6 -4 -2 0

time = 8.839 Myr
number of blocks = 12265
AMR levels = 6

Gray & ES (2010)
Globular Cluster Mass/Sizes

Disk shocking
\[ t \sim r_{1/2}^{-3} \cdot M \cdot R \]

Evaporation
\[ t \sim r_{1/2}^{3/2} \cdot M^{1/2} \]

Dynamical Friction
\[ t \sim M^{-1} \cdot R^2 \]

Maximum mass is an intrinsic property of the initial GC population

Castellani & Caputo 1984
#2: No Dark Matter In GCs

Grillmair etal 1995

NGC 288

NGC 362

NGC 3201

Moore 1998

No DM

M/L=2

M/L=3
Late Time Distribution

- Binned final distribution and evolved it for an additional 200 Myrs
- Most of the mass merges into large clumps

Gray & ES (2010)
#3: Globular Cluster Metallicities

Double-peaked

\[[\text{Fe/H}] \sim -0.5 \pm 0.25\]
\[[\text{Fe/H}] \sim -1.6 \pm 0.35\]

Narrow range < \(\Delta Z \pm 0.1\)
In each GC (eg Sunzeff 1993)

Single generation of well-mixed gas
Subgrid Turbulence

Initial Model (Dimonte & Tipton 2006)
Expanded Model (ES et al 2008; Gray & ES 2011)
Deals with turbulence arising from:
  Rayleigh-Taylor, Richtmyer-Meshkov, & Kelvin-Helmholtz instabilities
2 Equation model:
  K -- Turbulent Kinetic Energy
  L -- Size of largest eddies

Gray & ES (2011a)
Subgrid Turbulence

Chem+Cooling+Turbulence in AMR context: crucial collection of capabilities not available anywhere else!

Gray & ES (2011a)
Evolution

0 Myrs

2.1 Myrs

4.2 Myrs

6.3 Myrs

Log(\rho) 10^{-26} to 10^{-21} g/cm^3

Log(T) 10K to 10^8 K

Log(X_{H2}) 10^{-5} to 10^{-2}

Log(Z) 10^{-4} to 10^{-0.5} Z_\odot
Evolution

Gray & ES (2011a)

7.0 Myrs

7.7 Myrs

11.2 Myrs

14.5 Myrs

Log(\rho) 10^{-26} \text{ to } 10^{-21} \text{ g/cm}^3

Log(T) 10^8 \text{ K} \text{ to } 10^8 \text{ K}

Log(X_{H2}) 10^{-5} \text{ to } 10^{-2}

Log(Z) 10^{-4} \text{ to } 10^{-0.5} \text{ Z}_\odot
Gray & ES (2011b)

**Parameter Study**

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Initial Total Mass

- $10^6 \, M_\odot$
- $3 \times 10^6 \, M_\odot$
- $10^7 \, M_\odot$
- $3 \times 10^7 \, M_\odot$

Final Baryonic Mass

- $4 \times 10^4 \, M_\odot$
- $4 \times 10^5 \, M_\odot$
- $1.6 \times 10^6 \, M_\odot$
- $4.8 \times 10^6 \, M_\odot$

-26 < Log($\rho$) < -21

Gray & ES (2011b)
Other Parameters

Dissociating Background: No impact, H2 is formed much too quickly

Shock energy: in general the higher the shock energy, the lower mass clusters are formed

Distance: The closer to the host, the more efficiently SF is induced. Very far away > 5-6 kpc little impact.

Concentration & Formation Redshift: Minor impact
Spin: No impact whatsoever

Gray & ES (2011b)
Gray & ES (2011b)

Vorticity (km/s/kpc)
Gray & ES (2011b)

Vorticity (km/s/kpc)

\[ \frac{D\vec{\omega}}{Dt} = \frac{\partial \vec{\omega}}{\partial t} + (\vec{V} \cdot \vec{\nabla})\vec{\omega} = (\vec{\omega} \cdot \vec{\nabla})\vec{V} - \vec{\omega}(\vec{\nabla} \cdot \vec{V}) + \frac{1}{\rho^2} \vec{\nabla} \rho \times \vec{\nabla} p \]

baroclinic contribution
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This is a very robust formation mechanism!

Gray & ES (2011b)
Lyman-alpha Emission (1.6×10^6 M_☉)

0.3” FWHM

0.1” FWHM

Total flux ≈ 10^{-18} ergs/s/cm^2
Small objects strongly correlated with larger objects

Elongated towards the large objects
Thanks!

I. Primordial star formation:
-- Happens over a wide range of redshifts
-- Large Ly-alpha EW-> Narrow HeII
-- Don’t accept composites; and don’t lose the faith!

II. Outflow induced star formation:
-- Occurs over a large range of parameter space
-- Could be a chance to observe the oldest GCs as they were formed
-- Small starbursts, clustered around big ones, elongated
-- Requires deep, high angular resolution imaging.