How the first stars shaped the first galaxies

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mostly work with
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Talk Outline

- First Objects are very massive isolated stars
- First stars: HII regions, Supernovae, BH accretion
- Properties of First Galaxies
- ISM and molecular cloud formation
- Why making Galaxies one star at a time?

- public version of enzo at: http://lca.ucsd.edu/portal/software/enzo
Initial Value Problem

- Initial Conditions: COBE/ACBAR/Boomerang/WMAP/CfA/SDDS/2DF/CDMS/DAMA/Edelweiss/... + Theory: Constituents, Density Fluctuations, Thermal History
- Physics: Gravity, MHD, Chemistry, Radiative Cooling, Radiation Transport, Cosmic Rays, Dust drift & cooling, Supernovae, Stellar evolution, etc.
- Transition from Linear to Non-Linear:
- Using patched based structured adaptive (space & time) mesh refinement
- Differs from current day star formation:
  - Complete ICs are known
  - Chemistry, cooling, B, known

\[
\frac{R_\odot}{R_{\text{Milky Way}}} \approx 10^{-12}
\]

\[
\frac{P_\odot, \text{Kepler}}{t_{\text{Hubble}}(z = 30)} \approx 10^{-12}
\]
Accretion Time

- \( \dot{M} = 1 \times 10^{-2} \)
- \( \dot{M} = 1 \times 10^{-3} \)

Dynamic range: \( 2 \times 10^{13} \)

Minimum grid size: \( 0.1 \) R\(_{\text{sun}}\)

16 cells per Jeans length

High density, temperature, equation of state, radiation transport corrections, collision induced emission.
Recap

First Stars are isolated and very massive

- Theoretical uncertainty: 30 - 300 solar mass

Many simulations with **four very different numerical techniques** and a large range of numerical resolutions have **converged** to this result. Some of these calculations capture over 20 orders of magnitude in density and reach the proto-stellar accretion phase!

Non-equilibrium chemistry & cooling, three body H2 formation, chemical heating, H2 line transfer, collision induced emission and its transport, and sufficient resolution to capture chemo-thermal and gravitational instabilities. Stable results against variations on all so far test dark matter variations, as well as strong soft UV backgrounds.

Perfectly consistent with observations!
Could have been a real problem!
Immediate consequences

- Entire mass range are strong UV emitters
- Live fast, die young. (2.7 Myr)
- Fragile Environment
  - Globular Cluster mass halo but ~100 times as large -> small $v_{\text{esc}} \sim 2 \text{ km/s}$
  - Birth clouds are evaporated
CALIFORNIA NEBULA, NGC1499
500 pc = 1,500 light years away
30 pc long
Xi Persei,肩负肩部的Mankib, Shoulder of Pleiades:
O7.5III
330,000 solar luminosities
~40 solar masses, Teff=3.7e4K
Focus on point sources
Abel & Wandelt 2002, MNRAS; Variable Eddington
tensors: Gnedin & Abel 2001, NewA
Latest: Abel, Wise & Bryan 06 ApJL
Keeps time dependence of transfer equation
Adaptive ray-tracing of PhotonPackages using
HEALPIX pixelization of the sphere. Photon
conserving at any resolution.
Parallel using MPI and dynamic load balancing.
Fully coupled with non-equilibrium chemistry and
hydrodynamics.

\[
\frac{1}{c} \frac{\partial I_\nu}{\partial t} + \frac{\partial I_\nu}{\partial r} = -\kappa I_\nu
\]

Transfer done along adaptive rays
Case B recombination
HII region

Early HII regions in 3D

Abel, Wise & Bryan 07 ApJL

3kpc, 1/4 box

$O$

Shea, Abel, Whalen & Norman 05

Redshift ~20

$\rho$

$T$

$x_e$

$f_{H2}$

Abel, Wise & Bryan 07 ApJL

$150pc$ ~ $3kpc$, $1/4$ box

O’Shea, Abel, Whalen & Norman 05
Insignificant BH accretion - no mini quasars through this process, nor pre-cursors of Quasars.
First few hundred million years: Cosmic Fireworks

~7 kpc

10,000 such patches make Milky Way ~ 1e5 popIII remnants early metal enrichment

halo masses at redshift stars form within them
First few hundred million years:

~7 kpc

10,000 such patches make Milky Way
~ 1e5 popIII remnants
early metal enrichment
Developing an ISM

SimB-SNe

$z = 16.8$

John Wise & Tom Abel 2007
(KIPAC)
HII regions starting to be confined inside galaxies

John Wise & Tom Abel (KIPAC)
Making Galaxies one Star at a Time

~$10^8$ solar mass galaxy
z~ 20
one star at a time
~ 20 massive stars in progenitor
radiative feedback only
2 kpc across

Simulation: John Wise & Tom Abel 2007
Number of stars:

- SimA-RT: 19 (11 within $r_{\text{vir}}$)
- SimB-RT: 29 (22 within $r_{\text{vir}}$)
- SimB-SN: 24 (4 within $r_{\text{vir}}$)
Baryon Fraction & Angular Momentum

John Wise & Tom Abel
(KIPAC)
Building galaxies one star at a time. Why now?

- JWST, ALMA, LOFAR, MWA, etc. will not be able to observe individual stars but the smallest high redshifts galaxies as yet.

- Target dates: 2013

- We can and should **predict the properties** of these first galaxies to unprecedented detail:
  - metals, stellar content, Lyman alpha strengths, nebular emission lines, etc. **before they are seen.**

- Elucidate first galaxies-Lyman alpha forest connection

- Compare with nearby fossil record in the meantime
Application to present day star formation: very promising!

30 solar mass cloud
jeans number ~ 1
Mach 2 decaying turbulence
thermal + turbulent pressure equilibrium with ambient medium
31 levels of refinement: 11 orders of magnitude in length dynamic range: dx ~ 5e8 cm
64 cells per jeans length corresponds to 1e6 SPH particles per jeans mass or
~ 1e13 SPH particles for traditional (non-splitting) scheme
This run takes a few days on 16 (old) processors

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New version of enzo:
Hydro: RK2, HLL+PLM
MHD with Dedner formalism
Neufeld et al. cooling, EOSs
Multi-species chemistry
Radiation transport
Wang & Abel 2007

Mass = 30 Msun
Density = 5.65e-22 g/cm^3
Radius = 2.932e18 cm = 0.95 pc
Temperature = 10 K, Mu = 2, Gamma = 1.4
Initial isothermal sound speed=0.203192 km/s
Surface density = 2.21e-3 g/cm^2
Medium Density = 5.65e-23 g/cm^3
The time unit is such that t=1 is exactly one initial free fall time

log10 Temperature

log10 Density
Summary

- Wide range of birth, life & death of the first massive stars are being explored on super computers. Second generation primordial stars have lower mass than the first ones.

- HII regions of the first stars evaporate their host-halos leave a medium with \( \sim 1 \, \text{cm}^{-3} \) density but can we really assume no winds? Need better 3D stellar evolution calc.

- Enormous impact on subsequent structure formation
  - different angular momentum of gas vs. dark matter in first galaxies
  - turbulence/ISM
  - Black hole accretion limited
  - may provide a lot of the metalicity in quasar absorption systems
  - etc....

- Developed methods are very well suited to create star formation theories that will eventually confront observations