THE ROLE OF RADIATION PRESSURE IN HIGH-Z DWARF GALAXIES

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OUTLINE

• Enzo+Moray: Adaptive ray tracing and merging
• Pop III → II transition and dwarf galaxy formation
• The role of radiation pressure in dwarf galaxies
RADIATION TRANSPORT BY RAY TRACING
RT Equation along a Ray

- Consider point sources of radiation

- Initially, the radiation flux is split equally among all rays.

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

- \( P := \) photon flux in the ray
Adaptive Ray Tracing (Enzo+Moray)

- Ray directions and splitting based on HEALPix (Gorski et al. 2005)
- Coupled with (magneto-) hydrodynamics of Enzo
- Rays are split into 4 child rays when the solid angle is large compared to the cell face area
- Well-suited for AMR
- Can calculate the photo-ionization rates so that the method is photon conserving.
- MPI/OpenMP hybrid parallelized.

All development in https://bitbucket.org/enzo
Adaptive Ray Tracing (Enzo+Moray)

Abel & Wandelt (2002)
Wise & Abel (2011)

• H + He ionization (heating)
• X-rays (secondary ionizations)
• Lyman-Werner transfer (based on Draine & Bertoldi shielding function)
• Choice between energy discretization and general spectral shapes (column density lookup tables, see C²-Ray)
• See Mirocha+ (2012) for optimized choices for energy bins.
• Radiation pressure from continuum
• Choice between \( c = A_c, \infty \)
• Can delete a ray when its flux drops below some fraction of the UVB for local UV feedback.

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OVERCOMING $O(N_{\text{STAR}})$ :: RAY / SOURCE MERGING

- Sources are grouped on a binary tree.
- On each leaf, a “super-source” is created that has the center of luminosity.
- After the ray travel ~3-5 times the source separation, the rays merge.
- Recursive.
- Have run simulations with 25k point sources.

Okamoto et al. (2011)
Wise & Abel (in prep)
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Overcoming $O(N_{\text{star}})$ :: Ray / Source Merging

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SIMULATION SETUP: POP III $\rightarrow$ II
TRANSITION AND GALAXY FORMATION

- Small-scale (1 comoving Mpc$^3$) AMR radiation hydro simulation with Pop II+III star formation and feedback (1000 cm$^{-3}$ threshold)
- Self-consistent Population III to II transition at $10^{-4}$ Z$_\odot$
- Coupled radiative transfer (ray tracing: optically thin and thick regimes)
- 1800 M$_\odot$ mass resolution, 0.1 pc maximal spatial resolution
- Assume a Kroupa-like IMF for Pop III stars with mass-dependent luminosities, lifetimes, and endpoints.

\[ f(\log M) = M^{-1.3} \exp \left[ - \left( \frac{M_{\text{char}}}{M} \right)^{1.6} \right], \quad M_{\text{char}} = 100M_\odot \]
FoV = 1 c.m. Mpc
Pop III Metals

Pop II Metals

Temperature

Density

FoV = 1 c.m. Mpc

Friday, 14 December 12
Scatter at low-mass caused by environment and different Pop III endpoints

$M < 10^8 \, M_\odot$ halos
MASS-TO-LIGHT RATIOS

Scatter at low-mass caused by environment and different Pop III endpoints

$M < 10^8 \, M_\odot$ halos
• Isolated halo ($8 \times 10^7 \, M_\odot$) at $z=7$
• Quiet recent merger history
• Disky, not irregular
• Steady increase in $[Z/H]$ then plateau
• No stars with $[Z/H] < -3$ from Pop III metal enrichment
• Most massive halo ($10^9 \, M_\odot$) at $z=7$
• Undergoing a major merger
• Bi-modal metallicity distribution function
• 2% of stars with $[Z/H] < -3$
• Induced SF makes less metal-poor stars formed near SN blastwaves
Z-L RELATION IN LOCAL DWARF GALAXIES

- Average metallicity in a $10^6 \, L_\odot$ galaxy is $[\text{Fe/H}] \sim -2$

- Useful constraint of high-redshift galaxies, if we assume that this metal-poor population was formed during reionization.
VARYING THE SUBGRID MODELS

<table>
<thead>
<tr>
<th>$M_{\text{char}} = 40 , M_\odot$</th>
<th>No $H_2$ cooling (i.e. minihalos)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_{\text{crit}} = 10^{-5}$ and $10^{-6} , Z_\odot$</td>
<td>No Pop III SF</td>
</tr>
<tr>
<td>Redshift dependent Lyman-Werner background (LWB)</td>
<td>Supersonic streaming velocities</td>
</tr>
<tr>
<td>LWB + Metal cooling</td>
<td>LWB + Metal cooling + enhanced metal ejecta ($y=0.025$)</td>
</tr>
<tr>
<td>LWB + Metal cooling + radiation pressure</td>
<td></td>
</tr>
</tbody>
</table>
RADIATION PRESSURE FROM CONTINUUM ABSORPTION

- Acceleration is added to the cell from the absorbed radiation (hydrogen- and helium-ionizing and X-rays).

\[ dp_{rp} = \frac{dP E_\gamma}{c} \hat{r} \]
\[ da_{rp} = \frac{dp_{rp}}{dt \rho V_{cell}} \]

- where \( dP \) is the number of photons absorbed in the cell.

- In Enzo+Moray, acceleration from radiation is saved as 3 more grid fields.
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\[
p_\gamma = \frac{E}{c}
\]

Friday, 14 December 12
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RADIATION PRESSURE FROM CONTINUUM ABSORPTION

- Radiation pressure on dust grains increases the momentum transfer by the number of absorptions for a single photon, $f_{\text{trap}}$. For many scatterings, $f_{\text{trap}} \sim v/c$.

- Krumholz & Thompson (2012) found that $f_{\text{trap}} \approx \Sigma a_{\text{grav}}/(F_0/c) - 1$ and is lower than the IR optical depth.

- We do not consider dust in this calculation, but $\tau_{\text{IR}} \ll 1$ in this simulation.
EFFECTS OF RADIATION PRESSURE

$M_{\text{vir}} = 3 \times 10^8 M_\odot$ GALAXY AT $z = 8$

- Base
- Metal cooling
- Rad. pressure

Temperature [K]
- $10^4$
- $10^3$
- $10^{-1}$
- $10^{-2}$
- $10^{-3}$
- $10^{-4}$

Density [g/cm$^3$]
- $10^{-26}$
- $10^{-24}$
- $10^{-22}$
EFFECTS OF RADIATION PRESSURE

AVG. METALLICITIES IN DENSITY-TEMPERATURE SPACE

\[
\begin{array}{cccc}
10^{-28} & 10^{-26} & 10^{-24} & 10^{-22} \\
10^{1} & 10^{2} & 10^{3} & 10^{4} \\
10^{5} & 10^{6} & 10^{7} & \\
\end{array}
\]

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H$_2$ cooling to $T \sim 1000$ K. Local UV radiation field prevents cooling to 300 K.

Metal-rich ejecta “trapped” in cold, dense gas. Little mixing.

Radiation pressure aids in dispersing metals to the ISM.

JHW+ (2012 MNRAS v427)
BASELINE AT $z = 8$

Main Limitation:

- Lacking metal cooling
- Soft UV background
(Re-)introducing typical overcooling problem during initial star formation at $M \sim 10^8 M_\odot$

Causes over-enrichment – nearly solar metallicities.

Doesn’t match with $z = 0$ dwarfs, *but* this could be incorporated into a bulge.
SOFT UVB + METAL COOLING + RAD. PRESSURE

Momentum transfer from ionizing radiation

No treatment of radiation pressure on dust → lower limit on its effects

SF decreases because dense gas is further dispersed.

Enhanced metal mixing, resulting in an average metallicity of $10^{-2} Z_\odot$
Feedback from radiation pressure more effectively disperses metal-rich ejecta and produces a galaxy on the mass-metallicity relation.
Slice of acceleration due to momentum transfer from ionizing photons only, i.e. not including dust opacity.
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EFFECTS OF RADIATION PRESSURE
RADIAL VELOCITIES (OVERCOOLING $\rightarrow$ DECREASED SF)

- Reverses infall, increases turbulent motions, and decreases SF in the inner 100 pc.

- In rad. pressure simulations, $v_{\text{rms}} \sim V_c$

  compared to 25% without it.
SUMMARY

• Pop III supernova feedback enriches the first galaxies to a nearly uniform $10^{-3} \, Z_{\odot}$ but is the demise of Pop III stars.

• The gas depletion, IGM pre-heating, and chemical enrichment all have impacts on the properties of the first galaxies.

• Radiation pressure plays an important role in regulating star formation in the first galaxies through driving turbulence and allowing SN feedback drive outflows more efficiently.