Radiative feedback in cosmological simulations of galaxy formation

Sebastian Trujillo-Gomez

in collaboration with:
Anatoly Klypin (NMSU)
Daniel Ceverino (UA Madrid)
Pedro Colin (UNAM)
Joel Primack (UCSC)

Santa Cruz Galaxy Workshop - August 14, 2012
Motivation

Radiation pressure expected to have 3-fold effect on galaxy formation:

1. disruption of molecular clouds before SNe/ regulation of SF (Hopkins+11)
2. provide turbulence in MCs (Krumholz+12)
3. drive (warm) gas outflows at high-z (Murray+11)

radiative feedback in hydroART:

\[ F_{\text{rad}} = (\tau_{\text{UV}} + \tau_{\text{IR}}) \frac{L}{c} \]  
\[ P_{\text{rad}} = \frac{F_{\text{rad}}}{r^2} \]  
\[ \tau_{\text{IR}} = \Sigma_{\text{gas}} \kappa_{\text{IR}} \]  

(Murray+10)  
(Hopkins+11)

estimate \( L \sim 100P_{\text{SN}} \) per solar mass for \( \sim 3\text{Myr} \) (STARBURST99)

-> no free parameters
The simulations

in a fully cosmological setting, we would like to know if radiation pressure is able to:

1. drive massive outflows
2. prevent formation of a massive bulge
3. regulate SF
4. reduce the baryon fraction

<table>
<thead>
<tr>
<th>run</th>
<th>volume</th>
<th>redshift</th>
<th>halo mass</th>
<th>$R_{\text{vir}}$</th>
<th>resolution (proper)</th>
<th>SF model</th>
<th>FB model</th>
<th>$\tau_{\text{UV}}$</th>
<th>$\tau_{\text{IR}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW_SN</td>
<td>10 Mpc$^3$</td>
<td>z=3</td>
<td>$1.8 \times 10^{11}$ M$_{\odot}$</td>
<td>45 kpc</td>
<td>19 pc</td>
<td>$n_{\text{SF}} = 1 \text{cm}^{-3}$</td>
<td>SN+stellar winds</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>MW_SN+RP</td>
<td>10 Mpc$^3$</td>
<td>z=3</td>
<td>$1.8 \times 10^{11}$ M$_{\odot}$</td>
<td>45 kpc</td>
<td>19 pc</td>
<td>$n_{\text{SF}} = 1 \text{cm}^{-3}$</td>
<td>SN+stellar winds+RP</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>dwarf_SN+RP</td>
<td>10 Mpc$^3$</td>
<td>z=0</td>
<td>$3.0 \times 10^{10}$ M$_{\odot}$</td>
<td>80 kpc</td>
<td>38 pc</td>
<td>$n_{\text{SF}} = 6 \text{ cm}^{-3}$</td>
<td>SN+stellar winds+RP</td>
<td>1</td>
<td>50</td>
</tr>
</tbody>
</table>

$\tau_{\text{IR}} \sim 50$ gives maximum possible radiative forcing
**MW: mass distribution**

**MW_SN:**
- $M_{\text{stars}} = 6.8 \times 10^9 \, M_\odot$
- $M_{\text{gas}} = 3.0 \times 10^9 \, M_\odot$ (~50% cold)

**MW_SN+RP:**
- $M_{\text{stars}} = 4.5 \times 10^8 \, M_\odot$
- $M_{\text{gas}} = 5.2 \times 10^9 \, M_\odot$ (~30% cold)
MW: mass distribution

RP prevents runaway collapse of gas to center

\( V_{\text{circ}} = 200 \text{ km/s} \)

\( V_{\text{circ}} = \sim 130 \text{ km/s} \)

\( V_{\text{circ}} = 200 \text{ km/s} \)

Overcooling

Flat + DM dominated at all radii

Star formation drastically reduced in central 1 kpc

Total DM gas stars

\( r \) (kpc)
**MW: gas properties - density**

**within galaxy**

- ISM dominated by SF gas
- More diffuse gas
- Gas piles up at high densities

**within virial radius**

- Less diffuse gas in CGM!
- SN
- SN+RP

**RP regulates star formation by preventing gas collapse**

-> galaxy dominated by diffuse phase

**but**

CGM becomes denser
MW: gas properties - radial flows

within galaxy

- RP increases galactic wind but gas is reaccreted
- => gas circulates in galactic fountains / prevents bulge buildup

within virial radius

- RP quenches accretion of halo gas into galaxy
- reduced feedback energy limits mass and velocity of large-scale outflows
MW: gas temperature profiles

- cold
- warm/hot
- warm
- hot

RP+SNe eject most of inner disk cold gas + heat it above a million K

RP reduces SFR
-> not enough total FB energy to heat halo
MW: baryon fractions

RP reduces cold baryon fraction to ~10% and reduces the stellar fraction to ~1.8%

However, baryons are pushed outside 10 kpc but kept within halo -> $f_{\text{bar}} = 1$
MW: star formation history

- 10x suppression of SFR early on
- Continuous suppression for > 2 Gyr

![Diagram showing star formation history](image)
dwarf: mass distribution

\[ M_{\text{stars}} = 1.4 \times 10^8 \, M_{\odot} \]
\[ M_{\text{gas}} = 1.5 \times 10^9 \, M_{\odot} \text{ (mostly cold within 10 kpc)} \]

Despite strong RP, extended massive stellar component builds up.

Strong RP feedback results in DM core - episodic gas blowouts?

RP depletes halo gas.

Central stellar density 2-3x larger than in massive model.

Very small amounts of gas in halo.
dwarf: mass distribution

- Total DM
- Gas
- Stars

slowly-rising, DM-dominated at all radii

\[ V_{\text{circ}} \approx 58 \text{ km/s} \]

\[ f_{\text{gas}} = \frac{M_{\text{gas}}}{M_*} \approx 10 \]

sits slightly above baryonic T-F relation
at $z=0$, very small amount of mass in galactic winds and considerable amount of (cold) accretion into CGM.
dwarf: gas temperature profiles

at $z=0$, dwarf has a multiphase gas disk and warm/hot CGM

no hot gas, some cold gas accreting from IGM
dwarf: baryon fractions

at z=0:
50% of cosmic baryons lost within virial radius
only ~18% of cosmic baryons locked in cold phase
only ~2% in stars

Behroozi+2012
dwarf: star formation history

most of the stellar mass assembled in last few Gyr

agrees with observations (Salim+07)

SN feedback alone does not produce rising SFR

Colin+2010
Conclusions

✓ RP feedback is able to strongly reduce and regulate the SF in massive galaxies and dwarfs

✓ It does so by ejecting/heating the disk gas in a continuous galactic fountain

✓ The formation of a massive bulge is completely suppressed at z > 3 in an M* galaxy

✓ RP produces a dwarf galaxy with slowly rising rotation curve

✓ In a dwarf’s shallow potential, even a modest stellar component is able to reduce the fraction of baryons within R_{vir} by 50%

✓ RP reduces the early SFR by a factor of ~10. It leads to a late buildup of the stellar component in dwarfs consistent with downsizing

➡️ In massive galaxies strong RP does not produce outflows

➡️ in a dwarf, the fraction of baryons locked in stars is ~2 times larger than predictions - sits slightly above BT-F
thanks