The Origin and Evolution of the Mass-Metallicity Relationship

Alyson Brooks
U Washington

Primary Collaborators:
F. Governato (UW), B. Willman (Harvard-Smithsonian CfA),
C. Brook (UW), UW N-body Shop
What are the Long Standing Problems of Galaxy Formation in a CDM context?

Issue: Baryon/DM interaction still not accurately understood in galaxy formation/evolution

Outline

• Gasoline Simulation Campaign

• Past Simulation Problems
  - Angular Momentum Catastrophe
  - Substructure Problem
  - “Downsizing” of Galaxies

• Results (M-Z Relation)
SDSS gri-composite images from three galaxy simulations at $z=0$

Image by C. Brook, using mock broadband “observations” created with Sunrise, courtesy P. Jonsson.
Past Problems

The Tully-Fisher Relation

- Log $V_{\text{rot}}$ (km/s)
- Baryonic Mass ($M_{\odot}$)

Graphs showing $M_1$ vs. Log $V_{\text{rot}}$ on the left and Baryonic Mass vs. $V_{\text{rot}}$ on the right, with data points for GAL1, MW1, and DWF1.
The Effects of Feedback, cont’d

Past Problems

Moore et al. (1999) 2x10^{12} M_☉ galaxy
Past Problems

Anti-Hierarchical Formation: “Downsizing” and CDM
Overcoming Long Standing Problems in Disk Formation

1) A physically motivated description of SN feedback

2) Dramatically increased resolution

250kpc across; resolution 0.3kpc

- Ram Pressure Stripping
- Gas Rich Satellites
- Hot Halo (Blue)
- Cold Gas in Disks
- High Velocity Clouds
Two main theories for origin of MZR:

1) Preferential metal loss from low mass galaxies

2) Low SFR in low mass galaxies
The Mass-Metallicity Relationship for Galaxies

Stellar Mass ($M_\odot$)

$12 + \log(O/H)$


$MZR$
Resolution Effects

![Resolution Effects Graph](image)
Origin of the MZR: the Role of Mass Loss

- Do our galaxies show evidence for mass loss?
  - UV background? SNe blowout? tidal stripping?

- Effective yields commonly used as mass loss indicator

For a “closed box”:

\[ Z = \text{metallicity} \]

\[ M_{\text{gas}} / M_{\text{(gas+star)}} \]

\[ \text{stellar yield} \]

Rearrange and use observed metallicity and gas fraction:

\[ \gamma_{\text{eff}} = Z / (\ln f_{\text{gas}}^{-1}) \]

Tremonti et al. (2004)
Origin of the MZR: the Role of Mass Loss

Find all the gas that ever belonged to a galaxy (within virial radius) back to $z=3$

Galaxies approach asymptotic, "closed box" yield when lost gas is considered

Lowest mass galaxies have lost $>90\%$ of their baryons

BUT this is NOT due to supernovae blowout!
1) $\gamma_{\text{eff}}$ approaches “closed box” value when SN feedback is off

2) B/DM with SN feedback off is still 70%. Less than 25% of baryon loss is due to SNe, rest due to UV background
Origin of the MZR: the Role of Mass Loss

• Find all the gas that ever belonged to a galaxy (within virial radius) back to $z=3$

• Including lost gas doesn’t change the slope of the MZR!

• Preferential metal loss at low masses is not the origin of the MZR
Despite having lost most of their baryons, our lowest mass galaxies have the highest gas fractions, due to low star formation efficiency!

Consumption Rate \((\text{SFR}/M_{\text{coldgas}})\) is two orders of magnitude lower for our lowest mass galaxies than highest.
In our simulations, star formation efficiencies are regulated by SN feedback.

Over-consumption of gas

Increased metallicities and stellar mass

---

**MZR: SF Efficiencies**

- Feedback
- No SN feedback

- Over-consumption of gas
- Increased metallicities and stellar mass

---

**Graphs:**
- Left: $f_{\text{gas}}$ vs. $V_{\text{max}}$ (km/s)
- Right: $12+\log(O/H)$ vs. Stellar Mass (M$_\odot$)
Conclusions

1) We overcome past problems of CDM simulations

2) With no additional tweaking of the parameters, we also match the observed MZR for galaxies

3) The origin of our MZR is lower star formation efficiencies for lower mass galaxies, and mass loss has little effect on the slope of the MZR

4) Mass loss does, however, lead to a trend in effective yields

5) Only up to ~25% of lost baryons in our lowest mass galaxies are blown out by SNe

6) In our simulations, star formation rates are regulated by feedback
Results

The Effects of Feedback, cont’d

![Graph showing the effects of feedback on baryon/dark mass fraction with total mass and UV radiation levels as parameters. The graph features different markers for UV off, UV on with different SN rates (0 and 0.4).]
Low resolution: disks heat and lose angular momentum to halo

Our Simulations

The Importance of High Resolution

DM particles within Virial Radius

Log $N_{DM}$

Year

1995 2000 2005

10% J loss

30% J loss

70% J loss

Low resolution: disks heat and lose angular momentum to halo
The CDM Angular Momentum Problem

Navarro & Steinmetz (2000)

Past Problems

Disks are too small at a given rotation speed

Disks rotate too fast at a given luminosity

Mass (dark and luminous) is too concentrated

Disks are too small at a given rotation speed

Navarro & Steinmetz (2000)
Feedback Model

Free Parameters: SN & Star Formation efficiencies

1e9 M☉

Gerritsen (1997)
Thacker & Couchman (2000)
Ostriker & McKee (1988)
Star Formation Histories

Results

[SFR (M$\odot$/yr) vs Time (Gyrs) graphs showing different star formation rates and timescales for various galaxies, labeled as GAL1, MW1, and DWF1.]
LMC HI distribution (Venn+Stavely Smith 2003)
The Effects of Feedback

Red: stars
Blue: gas

- Total Mass $3 \times 10^{12} M_\odot$
- Spin Parameter $= 0.035$
- $V_{\text{rot max}} = 270$ km/sec
- Last major merger $z=3$
- Frame size $\sim 200$ kpc

No Feedback

UV+SN Feedback
More Massive Galaxies Have older Stellar Populations

…but in CDM Massive Halos Assemble Later Than Smaller Ones

MacArthur, Courteau & Bell (2004)
Star Formation Histories

Results

<table>
<thead>
<tr>
<th>SFR (M(_\odot)/yr)</th>
<th>Time (Gyrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing SFR and Time relationship](image-url)
CDM predicts hundreds of subhalos within the DM halo of an Milky Way sized Galaxy.

About 10 have been observed within the Milky Way’s halo.
Our Simulations

PKDGRAV: Parallel N-body Tree Code
Gasoline: PKDGRAV+gas using smoothed particle hydrodynamics (SPH)
Physics: Gravity, Hydrodynamics, Shocks, Radiative Heating+Cooling, UV field
Subgrid Physics: Star Formation, Supernova Feedback, Stellar Winds, Metal Enrichment

Wadsley et al. (2004), New Astronomy