Co-rotation of Cold, Accreted Halo Gas in LCDM

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Motivation:

Cold gas accretion is expected in LCDM, but so far, no clear observational signature. (Can we find one in gaseous halo properties?)

How are cold gaseous halos built and maintained? Smooth? Mergers?

What are their properties? Redshift evolution? Radial dependence?

Can theoretical properties be confirmed by observations?
Our Simulations
Some stats:
WMAP3 cosmo: $\Omega_0=0.24$, $\Lambda=0.76$, $h=0.73$, $\sigma_8=0.77$, $\Omega_b=0.042$

$m_{\text{DM}}$, $m_{\text{gas}}$, $m_{\text{star}} \sim 3e5$, $4e5$, $1e5$ $M_{\odot}$, $N_p \sim 4$ million,
resolution $\sim 332$ pc. Final ($z=0$) halo mass $M_{\text{vir}} \sim 2.12$ $M_{\odot}$

‘Blast-wave’ feedback of Stinson et al. ‘06; Haardt & Madau ‘96 UV field; NOTE: no strong galactic outflows here.
Our Simulations

Cold Gas

Stars

z6.393
Galaxy + Halo properties:

- DM ~ 0.04 as expected
- gas ~ 0.1–0.2

Much harder to lose high ang. mom. gas after mergers

(Motivation for choice of R<100 kpc next slide)
Galaxy + Halo properties:

Note: different merger histories, impacts halo gas.

$M_{\text{gas}} \sim 10^{10} M_{\odot}$

“Cold” : $< 10^5$ K
“Hot” : $> 10^5$ K

$\lambda_{\text{DM}} \sim 0.04$ as expected

$\lambda_{\text{gas}} \sim 0.1$–$0.2$

Much harder to lose high ang. mom. gas after mergers
Observational Aside: CF vs. R, z

Covering Fraction of HI (fractional area where \( N_{\text{HI}} > 10^{16} \, \text{atoms/cm}^2 \)) depends strongly on which radius you choose.

\[ \text{CF}(<R) \sim e^{-R/R_{\text{gas}}} ; \ R_{\text{gas}} \sim 30-80 \, \text{kpc (comov)} \]

CF (within fixed radius) varies strongly with recent gas accretion activity.

Minor gas–rich mergers increase CF for longer
Observational Aside: CF vs. R, z

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Minor gas–rich mergers increase CF for longer
All this high angular momentum, cold halo gas is from accreted gas (no outflows)...

With $\lambda_{\text{gas}}$ so high, is there any coherent rotation of halo gas?

This gas eventually falls on to the disk and forms stars...

Any correlation between the halo gas kinematics and the rotation of the galactic disk?
Example: $z=0.8$

3d gas density

LOS velocity
Can cold halo gas be observed?

QSO → Cold gas → Image from Tripp & Bowen (2005)

D ~ 100 kpc (or less)

Yes, in absorption
Halo Gas Kinematics (Example)

R < 100 co-moving kpc ; z=0.8
% of observable LOS that rotate : ~ 90%
% of rotating lines that co-rotate: ~ 70%

Open Squares: Non-rot
Filled Circles: Rotation (in either direction)

Stellar Disk

200 kpc
Halo Gas Kinematics (Example)

R < 100 co-moving kpc; z = 0.8
% of observable LOS that rotate: ~ 90%
% of rotating lines that co-rotate: ~ 70%

Circle-dot: Co-rotation
Circle-X: Anti-rotation

Stellar Disk

200 kpc
### Dependencies:

<table>
<thead>
<tr>
<th></th>
<th>Orientation</th>
<th>Merger History?</th>
<th>Radius</th>
</tr>
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<tbody>
<tr>
<td><strong>Cover Fraction</strong></td>
<td>Weak</td>
<td>STRONG</td>
<td>STRONG</td>
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<tr>
<td><strong>Rotation</strong></td>
<td>Weak</td>
<td>None</td>
<td>None</td>
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<tr>
<td><strong>Co-rotation</strong></td>
<td>STRONG</td>
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<td>Weak</td>
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High Cover Fraction: small R, recent/fresh gas accretion


High Co-rotation: recent gas accretion (particular orientations)
Can this co-rotation be observed?

It has already been observed!

Our simulations (ranges give typical viewing angle variation):

- Non-rotation: 5–15%
- Rotation: 85–95%
- Co-rotation: 50–90%
- Anti-rotation: 10–50%

Observations (Combined sample of Steidel+ 02 & Kacprzak+ 10):

- Non-rotation: ~25%
- Rotation: ~75%
- Co-rotation: ~70%
- Anti-rotation: ~30%

Steidel+ 2002; Kacprzak+ 2010;

Compared kinematics of cold absorption gas (using Mg II lines) to galaxy rotation curve.

Image from Kacprzak+ ‘10
Summary

- $\lambda_{\text{gas}} \sim 2$–4 times higher than $\lambda_{\text{DM}}$. This gas is spun up by mergers, and fed by continuous, fresh infall.

- $M_{\text{gas}} \sim 10^{10} M_{\odot}$ for MW progenitors ($R < 100$ kpc).

- Covering fraction ($<R$) of cold halo gas falls off exponentially, but still detectable out to $\sim 100$ kpc.

- Covering fraction depends strongly on recent merger/gas accretion history of the galaxy.

- Cosmological gas accretion in LCDM inevitably leads to rotation (co-rotation) of halo gas with the galactic disk.

- This signature can be observed. The (limited) observations of Steidel+02 & Kacprzak+10 agree quite well with our simulations.