Dark Halo Mergers and Disk Survival

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MERGER HISTORIES OF GALAXY HALOS AND IMPLICATIONS FOR DISK SURVIVAL
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Kyle Stewart

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Most big galaxies in the universe come in the form of disks.

Disk galaxies have been notoriously difficult to form in LCDM simulations. (e.g. Navarro & White 94)

Doing better recently, but not there yet.

Different models suggest qualitatively different pictures for disk galaxy assembly:

- Quiescent formation
- Gas-rich *mergers*
- Accreted thick disks...

Abadi et al. 03
Brook et al. 04;
Robertson et al. 04, 06
Kaufmann et al. 07
Governato et al. 04, 07
Disks in a hierarchical cosmology?

Given the uncertain astrophysical inputs, we may ask a more conservative question:

Even if a thin disk could form... could it ever survive the expected bombardment?

Toth & Ostriker 92
Walker, Mihos, Hernquist 96
Velazquez & White 99
Font et al. 01
Gauthier et al. 06
A Standard Cartoon...

e.g. Somerville & Primack 99 ... Springel et al. 05... etc.
How minor are these mergers?

Can disks survive?

Stewart et al. 07
Late Type Fraction vs. Halo Mass

Weinmann et al. 06

SDSS halo/gp catalog

Late type classification:
- Color
- SSFR
- concentration

$M = 10^{12} M_{\odot}$

~70% Late-type fraction

~70%

Late type

Early type

Host Halo Mass

$M=10^{12} M_{\odot}$
Park et al. 07 SDSS

~30% Early-type fraction for $M_r \approx -20$
Kautsch, Gregel, Bazazza, & Gallagher 2006


Non-trivial fraction of disk galaxies are super-thin, no bulge at all!

Catalog of edge-on disk galaxies from SDSS

- w/ bulge ~34%
- intermediate ~50%
- flat. no bulge ~16%
Late-type bulges => Internal secular processes?

Suggests an even higher fraction of galaxies without significant mergers.
Also e.g. Kormendy 05

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The Milky Way

DM Halo: $M_0 \sim 1.4 \times 10^{12} \, M_{\odot}$

- **Disk**: $M_d \sim 4 \times 10^{10} \, M_{\odot}$
  Oldest stars, $\sim 10$ Gyr

- **Thick Disk**: $M_{td} \sim 10^9 \, M_{\odot}$
  Uniformly old $\sim 10$ Gyr

- **Bulge**: Mostly old $\sim 10$ Gyr

Klypin et al. 02; Wyse 04

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Stewart et al. 07

- LCDM, $\sigma_8 = 0.9$

- ART N-body
  L=80 $h^{-1}$Mpc box
  $N_p=512^3$

- 17,000 halos at $z=0$
  $M_0 = 10^{11}$-$10^{13} \, h^{-1} M_{\odot}$
  $m_{\text{min}} = 10^{10} \, h^{-1} M_{\odot}$

- BDM -- spherical overdensity halo finder.
Count mergers of infalling objects $m$ into halos of $z=0$ masses $M_0$

Count as fall within halo virial radius

Use absolute cuts on $m$ NOT ratios $m/M_z$
Average Mass Accretion Histories

- Rapid early accretion rate
- Small halos form earlier
- Well known (e.g. Wechsler et al. 02)

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How is mass accreted?

~1/10 events dominate mass growth.

For typical $10^{12} \, M_{\odot}$ halo:

- $M \sim 10^{11}$ mergers dominate mass buildup.
Cumulative # of accretions larger than $m$

Approximately self-similar in $m/M_0$

For typical $10^{12} M_{\text{sun}}$ halo:

- $\sim 1 \times 10^{11}$ merger
- $\sim 7 \times 10^{10}$ mergers
- Increasing #’s of smaller mergers
Fraction of halos with merger larger than $m$ since time $t$

10$^{12}$ $M_{\odot}$ halos in last 10 Gyr:

- ~70% have $m=10^{11}$ merger
- ~95% have $m=5.10^{10}$ merger

See Cohn & White 07 for similar result at $z=10$
Fraction of halos with merger larger than $m$ since time $t$

10^{12} M_{\odot} halos in last 10 Gyr:

- ~70% have $m=10^{11}$ merger
- ~95% have $m=5.10^{10}$ merger

larger than current mass of MW disk
Mass accreted since last large merger?

Final disk fraction: $\Delta M/M_0$?
Typically, small fraction of final mass is accreted since last large merger.
Merger fractions vs $z=0$ Halo Mass:

Very weak mass trend, more prominent for larger mergers
Universal instantaneous merger rates

Stewart

Fakhouri & Ma 07

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Observed Trends: Galaxy Type vs. Halo Mass
Likely driven by astrophysics, not halo merger rates
Why not use mass ratios? $m/M_z$

Most high $m/M_z$ events are small in an absolute sense.
Typically $m/M_0 \sim 0.5 m/M_z$
\[ M_0 = 10^{12} \, h^{-1} M_\odot \]

Fraction with merger since \( t \)

Lookback Time \( t \) [Gyr]

Redshift

\( M_0 \) vs. \( m/M > 0.1 \)
Summary: Lots of fairly large mergers

$10^{12} \, M_{\text{sun}}$ halos in last 10 Gyr:

- ~70% have an $m=10^{11}$ merger
- ~95% have at least one $m=5 \times 10^{10}$ merger

larger than current mass of MW disk
Evidence for merging in the MW?
Structures in the Milky Way Halo & Disk?

monoceros ring

Edge of Milky Way stellar disk

Galactic Center

Sun

Sagittarius (below plane)

20 kpc

Newberg et al. 02
Yanny et al.

Belokurov et SDSS

Sagittarius Stream (with fork)
Orphan Stream (of unknown parentage)
Monoceros stream
Spatial structure in stellar halo \(--\rightarrow\) Evidence for past accretions?

Bell et al. 2007

BJ05 realizations

Theory

Data

Bullock, Kravtsov, & Weinberg 2001
JSB & Johnston 05; Robertson et al. 05; Font et al. 05, 06; Johnston, JSB et al. 07

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• Outer edges of thick disk disturbed...

• Smooth fitting functions break down...

Also structures in MW thick disk:
Eggen 96; Gilmore et al. 02; Wyse et al. 06; Helmi et al. 06
M31

Diffuse structure in M31 halo...

Fardal, Guhathakurta et al. 06

Ferguson et al.,
Irwin et al.

R~40 kpc disk-like configuration of stars:
- ~30 km/s velocity dispersion
- Lags thin disk rotation by ~40 km/s
- Intermediate age stars (~ thick disk)

Ibata et al. 05
Brown et al. 06

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Disk Response to Infalling Dark Halos

Kazantzidis, JSB, Zentner, Kravtsov, Moustakas

astro-ph/07
1. Extract Merger History from high-resolution N-body simulations

Klypin et al. 01
Kravtsov et al. 04
Zentner et al. 05

2. Initialize well-resolved MW-type disk

Widrow & Dubinski 05

\[
\begin{align*}
\text{h} &= 250 \text{ pc} \\
\text{R}_d &= 2.8 \text{ kpc} \\
\text{f}_{\text{res}} &\sim 50\text{pc} \\
\text{N}_{\text{dm}} &= 2.10^6 \\
\text{N}_{\text{disk}} &= 10^6 \\
\text{N}_{\text{bulge}} &= 5.10^5 \\
\text{N}_{\text{sat}} &= 5.10^5
\end{align*}
\]
3. Simulate impacts with $M \sim (0.2-0.6) \, M_{\text{disk}} \sim (0.7-2) \times 10^{10} \, M_{\text{sun}}$.
Use Orbits, Masses, Density Profiles measured as they cross within 50 kpc.

<table>
<thead>
<tr>
<th>Model</th>
<th>$z$</th>
<th>$t$ (Gyr)</th>
<th>$M_{\text{sat}}$ ($10^{10}M_\odot$)</th>
<th>$V_{\text{peak}}$ (kms$^{-1}$)</th>
<th>$r_{\text{peak}}$ (kpc)</th>
<th>$r_{\text{tid}}$ (kpc)</th>
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<tr>
<td>G1S1</td>
<td>0.96</td>
<td>7.6</td>
<td>1.14 (32.6%)</td>
<td>42.4</td>
<td>6.9</td>
<td>24.8</td>
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<tr>
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<td>7.3</td>
<td>1.98 (56.6%)</td>
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<tr>
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<td>0.20</td>
<td>2.4</td>
<td>0.75 (21.4%)</td>
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Note:
Ignore 2 largest ($\sim 5-10 \times 10^{10} \, M_{\text{sun}}$) substructures to be conservative.
3. Simulate Impacts of all Substructures with $M>0.2M_{\text{disk}}$. Use Orbits, Masses, Density Profiles etc. from Simulation.

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Prograde, retrograde, & polar orbits

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<th>( V_{\text{peak}} ) ((\text{km} \text{s}^{-1}))</th>
<th>( r_{\text{peak}} ) ((\text{kpc}))</th>
<th>( r_{\text{tid}} ) ((\text{kpc}))</th>
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Impacts are generally quite radial, with max to min radii > 6:1

Prograde \((<90^\circ)\) and retrograde \((>90^\circ)\) orbits.
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Initial disk  | Final disk  | Final disk (deep)

Kazantzidis, JSB, Zentner, Kravtsov, Moustakas 07
MW Disk(s): Thin + Thick

- Thin vertical scale height, ~250pc, + thick disk component ~2.4kpc

\[ \Delta z(R) \propto \frac{\Delta e_z}{\Sigma_d(R)[\alpha \Sigma_d(R) + 2z(R)\beta \bar{\rho}_s(R)]} \]

\[ \Delta z \sim \Sigma^{-2}_{\text{disk}} \]
Interesting faint structures: ring, flare, loops

~Mon. Ring?

55 kpc

60 kpc
Worry: Largest impact was $\sim 2.1 \times 10^{10} \, M_{\odot}$

$\sim 70\%$ MW halos have a $10^{11} \, M_{\odot}$ merger in last 10 Gyr

Stewart et al. 2007
“A merger-driven scenario for cosmological disk galaxy formation”

Robertson, JSB et al. 06

Proof of principle:
- Mergers common in CDM halos & important in j-acquisition
- Stellar mergers make spheroids, destroy disks (Quinn et al. 93, Walker et al. 96)
- What about gas-rich mergers?

High gas fractions + efficient ISM feedback can allow disks to form from mergers
Small galaxies: more gas rich than big ones

satellites
Small, gas-rich galaxies merge to make disks?

larger, gas poor galaxies merge & produce spheroids?

satellites
Take Home Messages

- ~70% MW-size halos have a $m=10^{11} \, h^{-1}M_{\odot}$ merger in last 10Gyr

- ~95% MW-size halos have at least one $m = 5 \times 10^{10} \, h^{-1}M_{\odot}$ merger larger than current mass of MW disk

- More simulations necessary to test whether this is as bad as it seems.

- Smaller, $\sim 2 \times 10^{10} \, M_{\odot}$ events, may not be as ruinous as previously suspected.

- Gas rich mergers may provide an explanation. Or CDM is in trouble....
Conclusions

- ~70% of MW-size halos accrete objects that are significantly larger than MW disk
The Milky Way

- Thin disk contains old stars ~10Gy.
  - Quillen & Garnet 2000; Freeman & Bland-Hawthorn 2002
  - Nordstrom et al. (bigger sample) 2004

- Is such a configuration possible given a typical merger history?
Cohn & White 07

![Graph showing cumulative fraction vs. lookback time for different mass ratios at z=10 with TreePM method.]