Probing Galaxy Halos with Tidal Interactions

Kyoto University Astronomy Department
June 27, 2013
Galaxy Formation

Baryons cool & collapse in dark halo potentials. — White & Rees 78
Galaxy Formation

Baryons cool & collapse in dark halo potentials. — White & Rees 78

Strong feedback stops premature cooling. — WR78, etc.
Galaxy Formation

Baryons cool & collapse in dark halo potentials. — White & Rees 78

Strong feedback stops premature cooling. — WR78, etc.

Halo spin sets disk scale. — Fall & Efstathiou 80; Mo, Mao, & White 98
Galaxy Formation

Baryons cool & collapse in dark halo potentials. — White & Rees 78

Strong feedback stops premature cooling. — WR78, etc.

Halo spin sets disk scale. — Fall & Efstathiou 80; Mo, Mao, & White 98

OR: Cold flows inject baryons and angular momentum. — Dekel et al 09
Unresolved Issues

Dwarf galaxies are less common than predicted.

Some halos don’t have the expected power-law cusps.

How are halo and stellar mass related?

What governs the angular momentum of disks?

Do baryons modify dark halos?
Can Tails Constrain Dark Halos?

“As the mass and extent of the dark halo increase, tidal tails become shorter, less massive, and less striking, even under the most favorable conditions.” — Dubinski, Mihos, & Hernquist 96
“The ratio of the circular velocity to the escape speed correlates well with the tidal response.”

\[ \mathcal{E} \equiv \left( \frac{v_e(R)}{v_c(R)} \right)^2 \]

“The ratio of the circular velocity to the escape speed correlates well with the tidal response.”

“Long tails constrain potential well depth, not halo mass itself.”

— Barnes 99

“These constraints are potentially very powerful if dynamical modeling is combined with detailed observation.”

— Springel & White 99
Modeling Galactic Encounters

Find collisions of two normal spirals which reproduce the morphology and kinematics of an interacting system.
Find collisions of two normal spirals which reproduce the morphology and kinematics of an interacting system.
NGC 4676: The Mice

NGC 4676: True-Color RGB Image

"The Mice": Colliding Galaxies
NGC 4676: The Mice
NGC 4676: The Mice
## Encounter and Viewing Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameters</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit</td>
<td>$p, e, \mu$</td>
<td>3</td>
</tr>
<tr>
<td>Disk Angles</td>
<td>$i_1, \phi_1, i_2, \phi_2$</td>
<td>4</td>
</tr>
<tr>
<td>Time</td>
<td>$t$</td>
<td>1</td>
</tr>
<tr>
<td>View</td>
<td>$\theta_X, \theta_Y, \theta_Z$</td>
<td>3</td>
</tr>
<tr>
<td>Scale</td>
<td>$\mathcal{L}, \mathcal{V}$</td>
<td>2</td>
</tr>
<tr>
<td>Center</td>
<td>$X_c, Y_c, V_c$</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>16</strong></td>
</tr>
</tbody>
</table>

This does not include the parameters for the initial galaxies!
NGC 4676: Parameter Correlations

The figure shows scatter plots of various parameters against time (t) for NGC 4676. The parameters include:

- P
- $\theta_x$
- $\psi$ (km/s)
- $\psi_c$
- $\theta_y$
- $\zeta$ (kpc)

Each parameter is plotted against time across six different subplots, with different colors and symbols representing different data points or categories.
NGC 4676: Time Scales
Galaxy Models: Construction

Halo: “NFW” profile with smooth taper.

\[ \rho_h(r) \propto \begin{cases} 
  r^{-1} (r + a_h)^{-2} , & r \leq b_h \\
  C_h r^{-\beta} e^{-r/a_h} , & r > b_h 
\end{cases} \]

Disk: exponential–isothermal profile.

\[ \rho_d(R, z) \propto e^{-\alpha R} \text{sech}^2(z/z_d) \]

Bulge: steep-cusp profile (Jaffe 83).

\[ \rho_b(r) \propto r^{-2} (r + a_b)^{-2} \]
Galaxy Models: Parameters

1. "Stellar fraction" (disk + bulge)

\[ f_* \equiv \frac{(M_d + M_b)}{(M_d + M_b + M_h)} = 0.2, 0.1, 0.05 \]

2. Halo concentration

\[ c \equiv \frac{b_h}{a_h} = 4, 8, 16 \]

3. Halo:Disk scale ratio

\[ \alpha a_h = 1.2, 1.5, 1.875, 2.4, 3.0, 3.75, 4.8, 6.0 \]

4. Bulge (optional)

\[ \frac{a_b}{a_h} = 0.16 \quad \quad \frac{M_b}{M_d} = 1/3 \]
Models without Bulges

$c = 16$

$f_s = 0.2, c = 8$

$c = 4$

$f_s = 0.1, c = 8$

$c = 16$

$f_s = 0.05, c = 8$

$c = 4$

$c = 6$

$c = 4.8$

$c = 3.75$

$c = 30$

$c = 24$

$c = 1.875$

$c = 15$

$c = 1.2$
Models with Bulges

\[ a_h = 3.75 \]

\[ a_h = 4.8 \]

\[ a_h = 3.75 \]

\[ a_h = 6 \]

\[ a_h = 6 \]

\[ a_h = 6 \]
Bar Instability

Detect by measuring moment of inertia within 25%, 50%, 75% radii.
Stability Tests (Models w/o Bulges)

- $a_h = 3.75$
- $a_h = 4.8$
- $a_h = 6.0$
- $a_h = 30$
- $a_h = 48$
- $a_h = 75$
- $a_h = 3.75$
- $a_h = 15$
- $a_h = 12$

$c = 16$
- $f_s = 0.2, c = 8$
- $f_s = 0.1, c = 8$
- $f_s = 0.05, c = 8$

$c = 4$
- $f_s = 0.2, c = 8$
- $f_s = 0.1, c = 8$
- $f_s = 0.05, c = 8$
Stability Tests (Models w/ Bulges)

\[ a_h = 3.75 \]
\[ a_h = 4.8 \]
\[ a_h = 6.0 \]
\[ a_h = 7.5 \]
\[ a_h = 9.0 \]

\[ f_s = 0.05, c = 8 \]  
\[ f_s = 0.1, c = 8 \]  
\[ f_s = 0.2, c = 8 \]  
\[ f_s = 0.4, c = 8 \]  
\[ f_s = 0.6, c = 8 \]  
\[ f_s = 0.8, c = 8 \]
Encounter Survey

Common parameters:

Orbital eccentricity: \( e = 0 \) (parabolic)

Pericentric separation: \( p = 2a_h \)

Disk angles: \( (i_1, \phi_1) = (0, 0) \) \( (i_2, \phi_2) = (71, 60) \)

With bulges
27 experiments sampling range of stable models.

Without bulges
5 experiments matching runs with bulges.
Encounter Survey (Models w/ Bulges)

- $c = 16$, $f_\ast = 0.2$, $c = 8$
- $c = 4$
- $c = 16$, $f_\ast = 0.1$, $c = 8$
- $c = 4$
- $c = 16$, $f_\ast = 0.05$, $c = 8$
- $c = 4$

- $\alpha_{\text{in}} = 4.8$
- $\alpha_{\text{in}} = 3.75$
- $\alpha_{\text{in}} = 3.0$
- $\alpha_{\text{in}} = 2.4$
- $\alpha_{\text{in}} = 1.875$
- $\alpha_{\text{in}} = 1.5$
- $\alpha_{\text{in}} = 1.2$
Encounter Survey (Models w/o Bulges)
"Legacy Model"

\[ c = 16 \quad f_\ast = 0.2, c = 8 \quad c = 4 \quad c = 16 \quad f_\ast = 0.1, c = 8 \quad c = 4 \quad c = 16 \quad f_\ast = 0.05, c = 8 \quad c = 4 \]
Quantifying Tidal Response

Define disk material which reaches a distance from its parent galaxy, $d > 10 \alpha^{-1}$, as belonging to a tidal feature (cf. SW99).

$$f_{\text{tidal}} \equiv \frac{M_{\text{tidal}}}{M_d}$$

Feature classification — measure two angles:

- $\cos \psi_P < 0$ and $\cos \psi_P > 0$
- $\cos \psi_a < 0$ (tail)
- $\cos \psi_a > 0$ (ambig)
- $\cos \psi_a > 0$ (bridge)
\[ f_\ast = 0.2, \quad c = 4, \quad \alpha a_h = 3 \]
$f_* = 0.1$, $c = 4$, $\alpha a_h = 1.875$
\[ f_\ast = 0.1, \quad c = 4, \quad \alpha a_h = 1.875 \]

\[ d > 6 \alpha^{-1} \]
\[ f_* = 0.1, \quad c = 16, \quad \alpha a_h = 3.75 \]
SW99 correlate tidal response with the ratio of escape to circular velocity, using

\[ E \equiv \left( \frac{v_e(R)}{v_c(R)} \right)^2 \text{ evaluated at } R = 2 \alpha^{-1} \]

I prefer an equivalent parameter:

\[ \xi \equiv \frac{v_c(R)}{\sqrt{-2\Phi(R)}} = \sqrt{\frac{2}{E}} \]

Note that \( \xi = 1 \) for Keplerian rotation, and \( \xi < 1 \) for galaxies.
Comparing Tidal Morphology

\[ f_\ast = 0.1 \]
\[ c = 4 \]
\[ \alpha a_h = 3 \]

\[ t = 1.8125 \]

\[ A_{ij} \]

\[ B_{ij} \]

\[ A_{ij} - B_{ij} + C \]

\[ r.a.d. \equiv \frac{\sum_{ij} |A_{ij} - B_{ij}|}{\sum_{ij} A_{ij} + B_{ij}} \]
Comparing Tidal Morphology

\[ f_\ast = 0.1 \]
\[ c = 4 \]
\[ \alpha a_h = 3 \]

\[ t = 1.8125 \]
\[ A_{ij} \]

\[ f_\ast = 0.1 \]
\[ c = 8 \]
\[ \alpha a_h = 2.4 \]

\[ t = 2.75 \]
\[ B_{ij} \]

\[ A_{ij} - B_{ij} + C \]

\[ r.a.d. \equiv \frac{\sum_{ij} |A_{ij} - B_{ij}|}{\sum_{ij} A_{ij} + B_{ij}} \]
Finding Good Matches

$\beta = 0.1, c = 4, \alpha a_h = 3$

$t = 1.8125$

$\beta = 0.1, c = 8, \alpha a_h = 2.4$
Best Matches: All Models w/ Bulges

$f_* = 0.1$

$f_* = 0.2$

$f_* = 0.05$
Morphological Equivalences

- $c = 16$, $f_* = 0.2$, $c = 8$
- $c = 4$
- $c = 16$, $f_* = 0.1$, $c = 8$
- $c = 4$
- $c = 16$, $f_* = 0.05$, $c = 8$
- $c = 4$
Conclusions

Escape parameter roughly correlated with tidal response (SW99).

Bulges have little direct effect on tidal features (SW99).

SW99 did not study bulge-stabilized galaxies, and somewhat underestimated halo effects in limiting tidal tails.

Bridges (tails) dominate tidal response at low (high) inclination.

Halo concentration and disk scale appear degenerate.

Next

Model-matching with a range of galaxy models.
Thank You!