Probing Galaxy Halos with Tidal Interactions
Galaxies and Dark Halos

\[ \frac{M_{\text{halo}}}{M_{\text{disk}}} \gtrsim 1 \]

\[ \frac{R_{\text{halo}}}{R_{\text{disk}}} \gtrsim 1 \]

\[ v \propto R^{-1/2} \]

- Observed
- Disk only
Gas cools and collapses in dark halo potentials. — White & Rees 78

Gravitational Clustering
Galaxy Formation

Gas cools and collapses in dark halo potentials. — White & Rees 78

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

Gas cools and collapses in dark halo potentials. — White & Rees 78

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

Gas cools and collapses in dark halo potentials. — White & Rees 78

Strong feedback stops premature cooling and collapse. — 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
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 determines the angular momentum of disk galaxies?

Do baryons modify dark halos? How??
GALACTIC BRIDGES AND TAILS

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ABSTRACT

This paper argues that the bridges and tails seen in some multiple galaxies are just tidal relics of close encounters. These consequences of the brief but violent tidal forces are here studied in a deliberately simple-minded fashion: Each encounter is considered to involve only two galaxies and to be roughly parabolic; each galaxy is idealized as just a disk of noninteracting test particles which initially orbit a central mass point.

As shown here, the two-sided distortions provoked by gravity alone in such circumstances can indeed evolve kinematically into some remarkably narrow and elongated features: (i) After a relatively direct passage of a small companion, the outer portions of the primary disk often deform both into a near-side spiral arm or “bridge” extending toward this satellite, and into a far-side “counterarm.” (ii) A similar encounter with an equal or more massive partner results typically in a long and curving “tail” of escaping debris from the far side of the victim disk, and in an avalanche of near-side particles, most of which are captured by the satellite.

Besides extensive pictorial surveys of such tidal damage, this paper offers reconstructions of the orbits and outer shapes of four specific interacting pairs: Arp 295, M51 + NGC 5195, NGC 4676, and NGC 4038/9. Those models can be found in the fairly self-explanatory figures 19, 21, 22, and 23.

Also discussed are some closely related issues of eccentric bound orbits, orbital decay, accretion, and forced spiral waves.
Orbit Decay

1. Spherical halos approach
Orbit Decay

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2. Tidal forces stretch halos
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3. Elongated halos are torqued
Orbit Decay

1. Spherical halos approach
2. Tidal forces stretch halos
3. Elongated halos are torqued
4. Halos spin up as orbit decays
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

\[ f_* = \text{stellar mass fraction} \]
“Long tails constrain potential well depth, not halo mass itself.”
— Barnes 99

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

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

“These constraints are potentially very powerful if dynamical modeling is combined with detailed observation.”
— Springel & White 99
Find collisions of two normal spirals which reproduce the morphology and kinematics of an interacting system.
Modeling Galactic Encounters

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

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<td>$X_c, Y_c, V_c$</td>
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<tr>
<td>Total</td>
<td></td>
<td>16</td>
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</tbody>
</table>

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

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

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)

\[ a_b/a_h = 0.16 \quad M_b/M_d = 1/3 \]
Models with Bulges

- $a_h = 3.75$
- $a_h = 4.8$
- $a_h = 6.0$
- $a_h = 7.5$
- $a_h = 16$
- $a_h = 18$
- $a_h = 24$
- $a_h = 30$
- $a_h = 37.5$
- $a_h = 48$
- $a_h = 60$

- $c = 16$
- $c = 4$
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- $f_s = 0.2$, $c = 8$
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- $a_h = 2.4$
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- $f_s = 0.1$, $c = 8$
- $f_s = 0.05$, $c = 8$
- $f_s = 0.1$, $c = 8$

- $a_h = 0.25$
- $a_h = 2.4$
- $a_h = 3.0$
- $a_h = 3.75$
- $a_h = 4.8$
- $a_h = 6.0$
- $a_h = 7.5$
- $a_h = 16$
- $a_h = 18$
- $a_h = 24$

- $f_s = 0.2$, $c = 8$
- $f_s = 0.1$, $c = 8$
- $f_s = 0.05$, $c = 8$
- $f_s = 0.1$, $c = 8$
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- $f_s = 0.1$, $c = 8$
- $f_s = 0.05$, $c = 8$
- $f_s = 0.1$, $c = 8$
Bar Instability

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

- $a_h = 3.75$
- $a_h = 3.0$
- $a_h = 2.4$
- $a_h = 1.875$
- $a_h = 1.5$
- $a_h = 1.2$

- $c = 16$
- $f_s = 0.2, c = 8$
- $c = 4$
- $f_s = 0.1, c = 8$
- $c = 4$
- $f_s = 0.05, c = 8$
- $c = 4$

- $b/a$
- $t$

- $f_{\text{\nudl}} = 0.2, c = 8$
- $f_{\text{\nudl}} = 0.1, c = 8$
- $f_{\text{\nudl}} = 0.05, c = 8$

- $c = 16$
- $c = 4$
- $c = 4$
- $c = 4$
- $c = 4$
- $c = 4$

- $\alpha_{\text{\nudl}} = 60$
- $\alpha_{\text{\nudl}} = 48$
- $\alpha_{\text{\nudl}} = 37.5$
- $\alpha_{\text{\nudl}} = 30$
- $\alpha_{\text{\nudl}} = 24$
- $\alpha_{\text{\nudl}} = 18.75$
- $\alpha_{\text{\nudl}} = 15$
- $\alpha_{\text{\nudl}} = 12$
Stability Tests (Models w/ Bulges)

\[
a_h = 3.75
\]

\[
a_h = 6.0
\]

\[
a_h = 4.8
\]

\[
a_h = 3.75
\]

\[
a_h = 3.0
\]

\[
a_h = 2.4
\]

\[
a_h = 1.875
\]

\[
a_h = 1.5
\]

\[
a_h = 1.2
\]
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)
Encounter Survey (Models w/o Bulges)

- $c = 16$, $f_\alpha = 0.2$, $c = 8$
- $c = 16$, $f_\alpha = 0.1$, $c = 8$
- $c = 16$, $f_\alpha = 0.05$, $c = 8$
“Legacy Model”

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

\[ \alpha_{\phi_0} = 4.8 \quad \alpha_{\phi_0} = 3.75 \quad \alpha_{\phi_0} = 3.0 \quad \alpha_{\phi_0} = 2.4 \quad \alpha_{\phi_0} = 1.875 \quad \alpha_{\phi_0} = 1.5 \quad \alpha_{\phi_0} = 1.2 \]
\[ c = 16 \quad f_* = 0.2, \quad c = 8 \quad c = 16 \quad f_* = 0.1, \quad c = 8 \quad c = 4 \quad c = 16 \quad f_* = 0.05, \quad c = 8 \quad c = 4 \]

**B742 [0.05, 8.5, 2]**

\[ a h = 3.75 \quad a h = 3.0 \quad a h = 2.4 \quad a h = 1.875 \quad a h = 1.5 \quad a h = 1.2 \]
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:

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

\( d > 6 \alpha^{-1} \)
$f_\ast = 0.1, \quad c = 16, \quad \alpha a_h = 3.75$
Tidal Response: Correlations

bridge: $i=0$

bridge: $i=71$

tail: $i=0$

tail: $i=71$
Escape Parameters

SW99 correlate tidal response with the ratio of escape to circular velocity, using

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

evaluated at

$$R = 2 \alpha^{-1}$$

I prefer an equivalent parameter:

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

Note that $\xi = 1$ for Keplerian rotation, and $\xi < 1$ for galaxies.
Results Compared
Comparing Tidal Morphology

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

\[ t = 1.8125 \]

\[ A_{ij} \]

\[ B_{ij} \]

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

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

\[
\begin{align*}
  f_* &= 0.1 \\
  c &= 4 \\
  \alpha a_h &= 3
\end{align*}
\]

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

\[
\begin{align*}
  f_* &= 0.1 \\
  c &= 8 \\
  \alpha a_h &= 2.4
\end{align*}
\]

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

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

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

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

\[ t = 1.8125 \]

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

$c = 16, f_s = 0.2, c = 8$
$c = 16, f_s = 0.1, c = 8$
$c = 16$
$c = 4$
$c = 4, f_s = 0.05, c = 8$
$c = 4$
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!