Identikit 1: A Modeling Tool for Interacting Disk Galaxies

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Spiral Galaxy NGC 4414 in Canes Venatici. HST, NASA.
Spiral galaxy NGC 4594 in Virgo. HST, NASA.
Elliptical galaxy NGC 4486 in Virgo. CFHT.
Normal Galaxies

Observationally, the symmetric forms of normal galaxies are crucial to their classification (Hubble 1936).

Theoretically, the symmetric forms of normal galaxies vastly simplify dynamical descriptions:

1. Noether’s theorem: symmetries correspond to conserved quantities such as integrals of motion.

2. Jeans’s theorem: the distribution function of a galaxy depends only on integrals of motion: 
   \[ f(\vec{r}, \vec{v}) = f(E, I_1, I_2) \]
Colliding galaxies NGC 520. Gemini Observatory, AURA, NSF.
Colliding Galaxies

Tides during close encounters create long “bridges and tails”; participants eventually merge (Toomre & Toomre 1972).

Merging galaxies don’t contradict Hubble’s classification; mergers transform normal galaxies from one Hubble type to another.
A Model of NGC 4676

John Hibbard & Joshua Barnes
“the future just like the past would be present”

-- Pierre-Simon Laplace
Model or “Look-alike”?

“With four parameters I can fit an elephant!”

-- John von Neumann

Is matching the morphology and kinematics really enough to constrain a dynamical model? Or do multiple solutions exist?

(A single disk yields two distinct solutions; more information -- dust lanes, spiral winding -- is needed to resolve the degeneracy.)
A Possible Test of NGC 4676 Model?

All available dynamical information has already been used to construct the model, so purely dynamical tests are ruled out.

Star formation history may provide a non-dynamical test. If shocks trigger star formation, NGC 4676 should have had a global starburst at first pericenter, 150 to 200 Myr ago (Barnes 2004).

Spectroscopy of young star clusters yields accurate ages which can be used to test this prediction.
Chien, Barnes, Kewley, and Chambers (2007)
Modeling Galactic Collisions

Goal: construct a unique dynamical model matching the observed morphology and kinematics of a given system.

Observational data:
- Optical (morphology, dust)
- Hα (kinematics)
- H I (morphology, kinematics)
- CO (kinematics)

Dynamical model: completely specified by distribution function:
\[ f(\vec{r}, \vec{v})d\vec{r}d\vec{v} \equiv \text{mass in } d\vec{r}d\vec{v} \text{ at } (\vec{r}, \vec{v}) \]
Perspective Vision

If you see this figure as a cube, you have deduced a 3-D configuration from a 2-D data-set.

How is this possible?

1. Prior knowledge: you’ve seen cubes before.

2. Internal consistency: the solution has the symmetries of a cube.
Merging galaxies display no obvious symmetries, but the galaxies which fell together to form them were probably normal galaxies. Thus the original galaxies are still there, hidden in the present dynamical state of the merging system.
Model Parameters

| Parameters     | Variables | Count |
|----------------|-----------|-------|
| Orbit          | $p, e, \mu$ | 3     |
| Disk Angles    | $i_1, \omega_1, i_2, \omega_2$ | 4     |
| Time           |           |       |
| View           |           |       |
| Scale          |           |       |
| Center         |           |       |
| Total          |           | 16    |

Toomre & Toomre (1972)
# Model Parameters

|                | Parameters          | Total |
|----------------|--------------------|-------|
| Orbit          | $p, e, \mu$        | 3     |
| Disk Angles    | $i_1, o_1, i_2, o_2$ | 4     |
| Time           | $t$                | 1     |
| View           | $\theta_x, \theta_y, \theta_z$ | 3     |
| Scale          | $L, V$             | 2     |
| Center         | $X_0, Y_0, V_{z0}$ | 3     |
| Total          |                    | 16    |

The parameter set includes:

- Orbital elements ($p, e, \mu$)
- Disk angles ($i_1, o_1, i_2, o_2$)
- Time ($t$)
- View angles ($\theta_x, \theta_y, \theta_z$)
- Scale ($L, V$)
- Center coordinates ($X_0, Y_0, V_{z0}$)

Total parameters: 16
Model Matching (the Hard Way)

Pick initial conditions, \((t, \theta, \mathcal{L}, \mathcal{U}, X_0, Y_0, V_{z0})\), integrate forward in time, and compare to the observations.

Repeat until happy.
Galactic Identakit

1. Build spherical models with mass profile of bulge+disk+halo:

\[ M_s(r) = M_b(r) + M_d(r) + M_h(r) \]

2. Populate with test-particle disks.

3. Interactively select which disk to display after simulation has been run.

Tidal features are well-reproduced by test-particle disks; massive spherical models provide plausible rotation curves and roughly self-consistent orbital decay.
2a. Populate with ball of test particles on circular orbits.

3a. Interactively select and display test particles whose initial angular momenta are aligned with desired disks.
Artificial Merger Sample
Initial Conditions

Galaxy Model:
- Hernquist bulge (5% mass)
- Exponential disk (15% mass)
- NFW halo (80% mass)

N = 131072 particles

Encounter Parameters:
- Inclinations: $\cos(i_i) \in [-1, 1]$
- Arguments: $\omega_i \in [0°, 360°)$
- Pericenter: $p \in [0.6, 6] \alpha^{-1}$
- Eccentricity: $e = 1$
- Mass ratio: $\mu = 1$
Random Views

1. Pick a random time between 1\textsuperscript{st} and 2\textsuperscript{nd} passage.

2. Pick a random viewing direction.

3. Pick random values for $\mathcal{L}$ and $\mathcal{V}$.

4. Project disk particles on $(X,Y)$, $(X,V_z)$ and $(V_z,Y)$ planes.

5. Plot nuclear positions and velocities.
What is the inclination and argument of each disk?

In what direction are we looking?

How much time has elapsed since pericenter?

How close was the passage?

What are the length and velocity scale factors?
Identakit Matching

Identakit Parameters:
- Pericenters: \( p \in \{0.125, 0.25, \ldots, 1\} \cdot 6\alpha^{-1} \)
- Eccentricity: \( e = 1 \)
- Mass ratio: \( \mu = 1 \)
- Particles: \( N_{sphr} = 81920 \), \( N_{test} = 262144 \)

Use the same mass model used in artificial merger sample.

Match test particle distribution to three orthogonal projections of data cube.

Use nuclear coordinates as constraints to speed up search.
A Fair Fit

view: -7.8 182.7 300.6
time: d.38
disk1: 23.6 125.8 (97.0)
xField: d.17
disk2: 134.1 72.5 (85.7)
vField: d.88
reading data file r1250-x125_0460.dat
A Poor Fit
Results: Disk Inclinations

True vs. fit disk inclinations with respect to the orbital plane.

Color shows subjective evaluation of fit:
- good (18 fits)
- fair (12 fits)
- poor (6 fits)
Results: Disk Arguments

True vs. fit disk arguments with respect to separation at pericenter.

Symbol shows disk inclination:
- $30^\circ \leq i \leq 150^\circ$
- $i < 30^\circ$, $150^\circ < i$
Results: Disk Orientations

$\Delta_{spin} \equiv$ angle between true and fit spin vectors.

Median value for
- all fits: $\Delta_{spin} \approx 18^\circ$
- good fits: $\Delta_{spin} \approx 12^\circ$
Results: Viewing Angle

$\Delta_{\text{view}} \equiv$ angle between true and fit lines of sight.

Median value for
- all fits: $\Delta_{\text{view}} \approx 13^\circ$
- good fits: $\Delta_{\text{view}} \approx 12^\circ$
Results: Time Since Pericenter

Range of $t_{\text{fit}}/t_{\text{true}}$ values:

- all fits: half between 0.86 and 1.14
- good fits: half between 0.94 and 1.10
Range of $p_{\text{fit}}/p_{\text{true}}$ values:

- all fits: half between 0.79 and 1.25
- good fits: half between 0.81 and 1.19

Results: Pericentric Separation
Results: Length Scale

Range of $\mathcal{L}_{\text{fit}}/\mathcal{L}_{\text{true}}$ values:

- all fits: half between 0.86 and 1.17
- good fits: half between 0.91 and 1.17
Results: Velocity Scale

Range of $V_{fit}/V_{true}$ values:

- all fits: half between 1.05 and 1.15
- good fits: half between 1.05 and 1.13
A few pairs of parameters have significant correlations; an error in one may be correlated with -- or even compensate for -- an error in another.
Identakit 2.0

Identify a region in data cube, and back-track to determine which disk orientations can populate it.
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Identakit Limitations

1. Simulations are not fully self-consistent:

   a) Disk structures requiring self-gravity (bars, grand-design spirals) will not be reproduced.

   b) Orbit decay is independent of disk orientation.

2. Real galaxies have a range of rotation curve shapes (and hence, mass profiles); a single mass model is too limited.

3. Test particles are collisionless, while most kinematic tracers follow a specific phase of the gas (e.g., H\textsubscript{i}, H\alpha, CO).
Disk Stars vs. Gas Phases

Disk stars
Gas (all phases)
Gas (HI proxy)
Are Models Unique?

1. Can we determine a unique distribution function?

   Difficult even for a *single* galaxy; orientation and intrinsic shape are hard to constrain.

2. Can we uniquely determine values for the parameters of a specific model?

   Parameters for the “good” and “fair” fits (30/36 cases) are so close to the actual values that these models are essentially unique.

   Some of the “poor” fits (6/36 cases) are clearly not unique.
Summary

1. Merging galaxies contain “hidden” symmetries inherited from their progenitors; these make dynamical modeling practical.

2. Test-disk + massive-spheroid models can be used to rapidly explore the parameter space of galactic collisions.

3. Interactive fitting recovers accurate and nearly unique models in almost all cases.

4. Backtracking from populated regions in data cubes may offer a way to identify disk orientations consistent with tidal features.

5. Semi-automatic fitting schemes may work if good criteria for acceptable fits can be defined. Total automation seems unlikely.
Thank You!
Encounters Resolve Degeneracies
The “Tadpole” Galaxy

The “Tadpole” galaxy, UGC 10214. HST. NASA.