Oct 26, 2015

- Impact of environment on galaxies
  - Galaxy-ICM interactions = ram pressure sweeping
  - Galaxy-galaxy interactions = gravity
  - Galaxy-cluster interactions = gravity

- HW#7 is due Wed; it requires you to write out answers clearly and completely explaining your logic, so be sure you explain yourself.

- HW#8 will focus on the final projects
  - Review the topics; assignments made on Wed (10/28)

There is a handout today
# Astro3303 Final Projects

<table>
<thead>
<tr>
<th>WHO</th>
<th>Facility</th>
<th>Science topic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>JWST</td>
<td>Detecting the first stars and galaxies</td>
</tr>
<tr>
<td></td>
<td>LSST</td>
<td>Constraints on dark energy from supernovae</td>
</tr>
<tr>
<td></td>
<td>HERA (e.g. PAPER)</td>
<td>Detecting HI from the “Dark Ages”</td>
</tr>
<tr>
<td></td>
<td>eRosita</td>
<td>Obscured active nuclei in galaxies</td>
</tr>
<tr>
<td></td>
<td>CCAT+ALMA</td>
<td>The history of dust-obscured star formation across cosmic time</td>
</tr>
<tr>
<td></td>
<td>TMT/GMT/E-ELT</td>
<td>Resolved stellar population studies in the Virgo cluster</td>
</tr>
<tr>
<td></td>
<td>ngVLA</td>
<td>Mapping cold, star-forming gas in early galaxies</td>
</tr>
</tbody>
</table>
Clustering of Galaxies

- Clusters contain 100s to 1000s of galaxies per Mpc$^{-3}$ as well as hot (Temp$\sim$10$^8$ K) gas, detected as X-ray emission.
Interaction of a spiral galaxy with its environment

- Gravitational interaction: galaxy - cluster
- Gravitational interaction: galaxy - galaxy
- Ram pressure: galaxy ISM - intracluster medium (ICM)

VLA Survey of Virgo in Atomic Gas: VIVA
www.astro.yale.edu/viva/

(Kenney et al. 1995)

(Böhringer et al. 1994)

(Kenney et al. 2004)
Ram pressure sweeping

• Spirals in Virgo are HI deficient.
• Hydrodynamical simulations show effectiveness of ram pressure stripping
• Stripping occurs if $\rho_{ICM} V^2 > 2\pi G \Sigma_{gas} \Sigma_{stars}$

- Ram pressure exerted by stationary gas on moving galaxy
- $V$ is velocity of galaxy with respect to cluster

- Gravitational “restoring” force of stars and gas in galaxy
- $\Sigma$ is surface density

Vollmer et al. 2001
Ram Pressure Stripping

- Ram Pressure Stripping can remove the gas supply of galaxies that pass through clusters
  - Interaction between ISM and ICM
  - Could explain metal content of the ICM
  - Episodes of starburst?

Animation by Bengt Vollmer

- The arrow which appears represents the “turn-on” of ram pressure as the galaxy moves in the opposite direction (towards the cluster center, in the lower left)
Peculiar morphologies

What are the main processes responsible for morphological peculiarities?
Gravitational encounters
“N-body” simulations: binary stars

1. Adopt the masses of the 2 objects (so here N=2)

2. Adopt characteristics of the orbits (eccentricity, inclination, orientation)

3. Apply the laws of gravity to predict the relative positions of the two objects after every time step.
“N-body” simulations: Sun-Earth-Moon

1. Adopt the masses of the 3 bodies (so here $N=3$)

2. Adopt characteristics of the orbits (eccentricity, inclination, orientation)

3. Apply the laws of gravity to predict the relative positions of the $N$ objects after every time step.

- Each of the 3 bodies exerts a gravitational force on the other two
- Each of the 3 bodies feels the gravitational force from the other two
- They are all in motion!
Toomre & Toomre 1972

- The galaxy’s mass is concentrated at a point
- The outer disk particles are arranged in 5 rings
- They do not interact with each other (no self-gravity)
- All passages involve two galaxies that have a close, slow moving parabolic approach
- Each time unit is 100 million years

Although much more sophisticated codes exist today, T&T72 demonstrated the overall damage done by tides.
Toomre$^2$ results

- Galaxy encounters are not accidental; most pairs are bound already
- Direct encounters cause more damage than retrograde ones
- Tails (nice) are easier to make than bridges (messy)
- Viewing geometry is critically important
Chris Mihos’ GalCrash Applet

http://burro.cwru.edu/JavaLab/GalCrashWeb/
Toomre & Toomre found that retrograde passage (ones in the opposite direction to a galaxy’s spin) have little tidal effect.

Flat retrograde ($i=180^\circ$) parabolic passage of a companion of equal mass.
• Direct passages are more effective
• More damage from equal mass companion

Fig. 2.—A flat direct ($i = 0^\circ$) parabolic passage of a companion of equal mass

Fig. 4.—A flat direct ($i = 0^\circ$) parabolic passage of a quarter-mass companion
Unlike the above, the most famous "bridge" linking two galaxies now seems definitely a fraud. Certainly both M51 (= NGC 5194) and its companion NGC 5195 show major signs of tidal damage. But as we are about to demonstrate, that damage only completes the proof that NGC 5195 lies at present well behind M51.

To begin, we would like it clearly understood here that our immediate concern is not with the magnificent spiral structure seen in M51 within, say, 20 of its center. Rather, in our view much of the explicit tidal damage to M51 itself only commences

Fig. 20.—Auxiliary studies of M51. (a) The top row offers five face-on (β = 0°) views of the evolving shapes of three test-particle rings of initial radii 0.2, 0.4, and 0.6\(R_{\text{min}}\), after being perturbed by an inclined \(i = -70°, \alpha = -15°\), elliptic \(e = 0.8\) passage of a companion of one-third mass. Also shown, at times \(t = 2.0\) and 2.8, are the corresponding shapes from instances where the mass ratio of the satellite to the primary was assumed one-half and one-fifth; in those cases, the original radius of the outermost ring was altered to 0.5 and 0.65\(R_{\text{min}}\), respectively. (b) Slightly tilted (\(\lambda = 65°, \beta = -20°\)) and \(\pm\)-enlarged view of the above \(t = 2.4\) configuration. It excludes the 0.2 and 0.7\(R_{\text{min}}\) particles, but it includes two additional rings from 7/15 and 8/15 \(R_{\text{min}}\). The left-hand picture has been decomposed on the right into its four constituent rings; the italicized numbers there are the Doppler velocities of various particles, relative to the primary, obtained after scaling the similar speed of the satellite to \(\pm 110\) km s\(^{-1}\).
Fig. 21.—Model of the recent encounter between M51 and NGC 5195. Shown here at $t = 2.4$ are three mutually orthogonal views of the consequences of a highly elliptic $e = 0.8$ passage of a supposedly disklike "5195." This satellite was chosen to be one-third as massive, and of exactly 0.7 times the linear dimensions, of the "5194" primary—which itself contains particles from initial radii $0.2(0.05)0.4(0.033)0.633R_{\text{min}}$. The orbit plane differs by an angle $i_b = -70^\circ$ from the initial spin plane of the larger disk and by $i_b = -60^\circ$ from that of the smaller; however, the arguments $\omega_4 = \omega_5 = -15^\circ$ of the pericenters were here kept identical, to make the above nodal axes $x_4$ and $x_5$ exactly antiparallel. The three views show the combined system as it would appear not only (b) to us ($\lambda_4 = 65^\circ$, $\beta_4 = -20^\circ$), but also edge-on to our sky from (a) the "north" ($-25^\circ$, $90^\circ$) and (c) the "west" ($65^\circ$, $70^\circ$) directions.
FIG. 13.—Results of four differently inclined passages of fixed argument $\omega = +60^\circ$. The top row depicts the $\beta = 0^\circ$ face-on appearances of these four severely perturbed disks at $t = 3.143$, whereas the bottom row shows how each object would look if viewed at tilt $\beta = 60^\circ$ from the same longitude $\lambda = 45^\circ$. 
### TABLE 3. Input parameters for the modeling.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>M81</th>
<th>M82</th>
<th>NGC 3077</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA (1950)</td>
<td>09^h^51^m^30^s</td>
<td>09^h^51^m^44^s</td>
<td>09^h^59^m^22^s</td>
</tr>
<tr>
<td>Dec. (1950)</td>
<td>+09°18'.3</td>
<td>+09°54'.9</td>
<td>+68°58'.5</td>
</tr>
<tr>
<td>Relative Velocity (km s^{-1})</td>
<td>0</td>
<td>+230</td>
<td>+36</td>
</tr>
<tr>
<td>Total Mass (10^{10}M_☉)</td>
<td>20</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Disk Radius (kpc)</td>
<td>36</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>Disk Inclination</td>
<td>59°</td>
<td>82°</td>
<td>45°</td>
</tr>
<tr>
<td>Disk P.A.</td>
<td>150°</td>
<td>28°</td>
<td>225°</td>
</tr>
<tr>
<td>a^1 (kpc)</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

^1 softening parameter in Plummer potential.
M81/M82 encounter
M81/M82/NGC3077 movie
Tails

• Unlike bridges, tails involve some particles escaping towards infinity.

• To form major tails, the galaxies should be similar in mass.

• Like bridges, tail making is less effective at higher inclination planes. Again, the difference between 0° and 30° is small.

• However, in higher inclinations, the tail is raised from the orbit plane. This allows the tails to be crossed, as in \textbf{NGC 4038/9 = “The Antennae”}.
Low velocity encounters (Tides, mergers)

The Antennae: NGC 4038/9. Optical wide field (left) + HST (right)
• Mass ratio ~1
• Disks shown in their original position.
• Each disk inclined 60° with respect to orbital plane
The Antennae (as observed)

http://www.cita.utoronto.ca/~dubinki/antennae/antennae.html
The Antennae (from the top)

http://www.cita.utoronto.ca/~dubinki/antennae/antennae.html
Galaxy mergers

Mergers

Arp 220: Classic ULIRG

Animation courtesy of J Barnes
"The Mice"

See http://www.ifa.hawaii.edu/~barnes/research/interaction_models/mice
Fig. 22.—Model of NGC 4676. In this reconstruction, two equal disks of radius $0.7R_{\text{min}}$ experienced an $e = 0.6$ elliptic encounter, having begun flat and circular at the time $t = -16.4$ of the last apocenter. As viewed from either disk, the adopted node-to-peri angles $\omega_A = \omega_B = -90^\circ$ were identical, but the inclinations differed considerably: $i_A = 15^\circ$, $i_B = 60^\circ$. The resulting composite object at $t = 6.086$ (cf. fig. 18) is shown projected onto the orbit plane in the upper diagram. It is viewed nearly edge-on to the same—from $\lambda_A = 180^\circ$, $\beta_A = 85^\circ$ or $\lambda_B = 0^\circ$, $\beta_B = 160^\circ$—in the lower diagram meant to simulate our actual view of that pair of galaxies. The filled and open symbols distinguish particles originally from disks A and B, respectively.
The Mice: a driven system

See http://www.ifa.hawaii.edu/~barnes/research/interaction_models/mice
Drop-through or head-on collisions
Chris Mihos' Cartwheel movie

See: http://burro.astr.cwru.edu/SSAnims/
Disk heating

http://burro.astr.cwru.edu/SSAnims/
How likely are encounters?

- Slow encounters are unlikely in dense clusters.
- Simulated passages are unlikely to be hyperbolic.
- Tails and bridges are the least observed in dense clusters.
- Close encounters unlikely in loose groups.
- Most tidal effects must have been created by galaxies that are gravitationally bound.

**Disruption damage**

- Tidal force \( F \propto r_p^{-3} \) where \( r_p \) is the separation at perigalacticon
- Duration \( T \propto r_p/v \) where \( v \) is the relative velocity
- In the impulse approximation, \((J = F*T)\), the “damage” is \( \sim 1/(r_p^2 v) \)
  
  \( \Rightarrow \text{slow close encounters do the most “damage”} \)
cD N4881 in Coma

cD = “cluster diffuse”

Much brighter than next brightest galaxy
cD galaxies

- In the cores of regular rich clusters (or at a density enhancement)
  - Local conditions are important
- Offset (too bright) from the luminosity function of normal galaxies
- Extensive (~1Mpc) stellar envelopes of low surface brightness
- Many have multiple nuclei

Cf. cD galaxy in Abell 3827
Suppose an object of mass $M$ is moving within a sea of other objects of mass $m$, with $m < M$.

As $M$ moves forward, the other objects are pulled towards it, with the closest ones feeling the strongest force.

This produces a region of enhanced density along the path of $M$, including a wake trailing it.

**Dynamical friction** = net gravitational force on $M$ due to others that opposes its motion.

Kinetic energy is transferred from $M$ to surroundings, thus reducing its speed.
Formation of a cluster like Virgo

Simulation by Ben Moore
Galaxy “harassment”

Multiple (high speed) encounters in clusters can also inflict “damage”

• Supporting evidence:
  – Intra cluster diffuse light (ICL)
    • Intergalactic stars, ~10-40% of the cluster stellar population (Feldmeier et al., 2003)
  – Tidal debris
    • e.g. Plumes and arc-like structures
    • The amount of tidal debris and ICL depends on local density, which supports the merger scenario (Combes, 2004)
  – Rings of star formation that are more common than two-armed spirals (Oemler et al., 1997)
    • Due to bars triggered during tidal interactions?

NGC 4696
Evolution of galaxies in Virgo

See: http://www.cita.utoronto.ca/~dubinski/rutgers/galaxies

• Cluster tides can be effective in stripping stars from galaxies and building up an intracluster stellar population

• See: http://astroweb.case.edu/craig/diffuse_light/diffuse_light.html

$\mu(V) < 21.5$

Galaxy Orbit: apocenter=1 Mpc pericenter=50 kpc
1M Disk + 250K Bulge + 1M Halo = 2.25M particles
Dubinski, Hayes, & Dieng

Mihos et al. 2005
Multiple rapid encounters in a cluster may also seriously impact galaxy evolution.

Blue: dark matter
Red: gas
Yellow: stars

Animation courtesy of G. Lake
Millennium Simulation
10,077,696,000 particles

(z = 0)