The Formation of the Local Group of Galaxies

Wherein Numerical Action Method and Backward Integration are used to Model the Trajectories of LG Galaxies

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Planes of galaxies in the LG

• PAndAS – 400 sq deg deep images of M31
  – 15/34 of satellites in thin plane 13 kpc rms.
• Most of the other galaxies near M31 lie in a second plane
• Satellite galaxies of MW also lie in a plane or 2.
• Centaurus A Group satellites also lie in two planes (Tully, 2013)
• Hammer (2013) suggests tidal debris can create thin planes.
• If so, then Missing Satellite Problem goes to crisis mode.
• Measurement of DM content of dwarfs unexplained.
• Why does the luminosity-metallicity relation continue into the dSphs?
NAM

**Numerical Action Method**
- Solve for orbits in a cosmological scenario where peculiar velocities arise from mutual gravitational interactions and initial velocities are consistent with linear perturbation theory.
- Trajectory follows cm of all DM particles now in each galaxy; Masses are constant over time.
- Halo softening: $|F_{ij}| = \{G \frac{M_i M_j}{r^2} \} \min(r/R_i,1) \min(r/R_j,1)$
- Add smooth distribution of particles (orphan particles)
- Use WMAP cosmological parameters.
Backtracking

• For low mass galaxies, we can integrate for $v(t)$ and $x(t)$ backwards in time from present position, but constrained that $v(z=z_{\text{init}})$ given by the potential field from the high mass galaxies.

• Since we do not know $p_m$’s, we must try all directions in the sky for the velocity (well, 1° intervals).

• Acceptable solutions are those with $v_{\text{pec}}(z=4) < 25$ km/s.

• Near major galaxies many solutions with very tight orbits, 2-5 simple solutions with 0-2 passes.

• Except, we know $p_m$ of M31, M33, IC10, and Leo I. And more to come! Hopefully.
Galaxy distribution map

- To model LG, need to know Virgo Mass, to model Virgo Mass need GA Mass.
- We created an input catalog of distances, cz, and brightnesses for 245 galaxies/groups/clusters < 200 Mpc.
- Typically we have 5% errors on individual galaxy distances out to 8 Mpc. (Cepheids, TRGB, RR-Lyrae etc)
- Beyond 8 Mpc we begin to use groups and clusters (TF relation, SBF).
- Beyond 25 Mpc just use clusters.
Hydra/Centaurus/Norma Flow
LSC FLOW (NAM SOL’N)
M33 Solution 1
co-moving LG Frame
M33 Solution 2
Leo I

Velocity\((z=4)\) error With \((SGL_v, SGB_v)\)
Observed Proper motions
M31, M33, IC10, LEO I
Output of M33 Soltn 2 model

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Observed Proper Motion</th>
<th></th>
<th>Model Proper Motions</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>( \mu_{sgr} ) ( \mu \text{ as yr}^{-1} )</td>
<td>( \mu_{sgr} ) ( \mu \text{ as yr}^{-1} )</td>
<td>( \mu_{sgr} ) ( \mu \text{ as yr}^{-1} )</td>
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<tr>
<td>m0 I</td>
<td>-81.87</td>
<td>-33.57</td>
<td>88.49</td>
</tr>
<tr>
<td>I31</td>
<td>-8.26</td>
<td>-3.48</td>
<td>8.96</td>
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<tr>
<td>C10</td>
<td>20.46</td>
<td>38.79</td>
<td>43.86</td>
</tr>
<tr>
<td>I33</td>
<td>32.92</td>
<td>28.87</td>
<td>43.79</td>
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</tbody>
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Opportunity knocks

• Galaxies in a plane must move roughly the same way to maintain the plane for significant duration.
• The easiest way to maintain the plane is for galaxies to move along the plane.
• Backtrack Procedure –
  – Do not vary distances or cz,
  – use M/L =50 for Spirals and 60 for ellipticals.
    • this provides enough attraction for M31’s cz
  – Vc = 240 km/s.
  – Ω_smooth = 0.11
  – Map in (SGL_V, SGB_V), take orbit with fewest windings, V(z=4) close to linear theory, and stays in its plane.
PLANE 1 BLUESHIFTED
Plane 1 Blueshifted
Plane 1
PANDAS
PANDAS plus orbits of some satellites
Plane 3
Plane 4
Plane 3 & 4
comoving coordinate
LSC frame
And27, N6789, N6946
Conclusions

- We have found orbits for 57 galaxies within 1.4 Mpc of the MW.
  - Solutions of M31, M33, IC10, LeoI are concordant with their newly observed proper motions.
- 4 Planes (2 at M31, 2 at the MW) hold 41/50 galaxies < 1.1 Mpc, provide new constraints on proper motions of galaxies.
- LG Satellite galaxies were embedded in Local Sheet at z=4 of 0.1 x .4 x 1 Mpc.
- This plane was broken down into ring.
- Many Plane 1 galaxies have been in plane 1 since z<4. Others have been pulled in by tidal field of MW.
- Plane 2 galaxies passed M31 in SGZ within the last Gyr and have reached turnaround in SGZ component. They are spreading out in the other two components.
More conclusions

- MW satellites
  - were restricted to small SG X range
    - M31 and Cen A snatched other galaxies.
  - Plane 3 is stretched out by Virgo Cluster tidal field
  - Plane 4 is stretched out by the MW motion in LSC frame.
- Satellite galaxies are arranged in planes which provides a more efficient mechanism for them to be cannibalized by the giants.
Plane 1 & Plane 2