The Local Group:
Then, Now, Forever, and Always

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The Great Andromeda Galaxy
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Acknowledgements

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See McConnachie et al. 2009 and many others
The Local Triangulum

M31

M33

The Milky Way

210 kpc

809 kpc

785 kpc
PAndAS map
courtesy Mike Irwin
Modeling Goals

Construct a Realistic Model of the Local Group Including the M31, M33, the Milky Way and Satellites

Use This Experimental Platform to Investigate The Dynamics of the Local Group Including Interactions and Satellite Tidal Disruption And Stream/Shell creation (In Progress...)

Galaxy models: Widrow et al. 2008
N-body: Dubinski 1996
Satellite data: Brasseur, Collins, McConnachie

From Crumb’s Illustrated Book of Genesis

Tuesday, June 26, 2012
Tidal Distortion of M33?

What is this stuff?

Did M33 interact with M31 recently? (Bekki 2008 has also considered an interaction re: the gas “bridge”)
Stellar Distribution Around M33

-2.0 < [Fe/H] < -1.0 dex

- ~1% in tidal extensions
- very low surface brightness
- low metallicity

\[ \mu = ? \text{mag sq.arcsec} \]

McConnachie et al. 2010
Figure 1. HI Distribution

The full arc as it emanates from the regular disk structure in Figure 1 is Wright's cloud and M33. They are separated in velocity space by only 20 km s\(^{-1}\), being 5 \(\times\) \(10^{20}\) cm\(^{-2}\) (e.g., Figure 9), or 16 kpc at the mass of M33 is over 250 km s\(^{-1}\) here (Wright 1979). Since the feature is largely confined within the 5 \(\times\) \(10^{20}\) cm\(^{-2}\), i.e., does not include the filament back to the central regions of the disk evident in future paper. There is no evidence for a direct link between north into M33's known warp and the northern arc here (Wright 1979).

The channel column density map of M33. Contours are 8 \(\times\) \(10^{18}\) cm\(^{-2}\) and spatially this cloud is known to be separated by only 20 km s\(^{-1}\) from the channels. Wright's cloud extends from the channels as low as 10 \(\times\) \(10^{18}\) cm\(^{-2}\) here (Wright 1979). All velocities are in the LSR reference frame.

\[ \Delta v \approx \pm 25 \text{ km s}^{-1} \]
\[ \Delta r \approx 16 \text{ kpc} \]

Approximate central value.
The Warped Disk of M33

Fig. 4.—Maps of flux and velocity residuals for the basic model Corbelli & Schneider 1997
M31-M33 Interaction

Panoramic View

Elapsed time 3.4 Gyr (70 Myr/s)
M33 interaction occurs about 2.5 Gyr ago
Orbital pericentre 50 kpc

Tuesday, June 26, 2012
M31-M33 Interaction

Panoramic View

Elapsed time 3.4 Gyr (70 Myr/s)
M33 interaction occurs about 2.5 Gyr ago
Orbital pericentre 50 kpc

100 kpc
10 kpc
25 kpc
M31-M33 Interaction

Panoramic View

Elapsed time 3.4 Gyr (70 Myr/s)
M33 interaction occurs about 2.5 Gyr ago
Orbital pericentre 50 kpc
M31-M33 Interaction

Panoramic View

Elapsed time 3.4 Gyr (70 Myr/s)
M33 interaction occurs about 2.5 Gyr ago
Orbital pericentre 50 kpc
Edge-on Views

M31 is mildly warped by encounter - maybe explains the observed warp?

M33 - outer disk is pulled into the orbital plane
- strongly warped disk
- consistent with the inferred gas warp
Fig. 11.—The density distribution of candidate RGB stars in the metallicity interval $-2.1 \leq \text{[Fe/H]} \leq -1.0$ dex, using an identical procedure to Figure 6. This metallicity cut was selected to optimally identify the M33 substructure. Black contours are 2, 5, 8 and 12$\sigma$ above the background, corresponding to estimated surface brightness limits of $\mu = ?$, $?$, and $?$, respectively. The gray contour is 1$\sigma$ above the background ($\mu = 33.5 \text{mag sq.arcsec}^{-2}$). Right panel: the colour image shows the same image as the left panel (now with log scaling). The contours show the HI column density distribution, as recently derived by Putman et al. (2009).

Andromeda I and III, and we use these galaxies to derive two relationships between star counts and integrated luminosity. We use the structural parameters for Andromeda I and III as measured by McConnachie & Irwin (2006), who measure integrated luminosities based on unresolved light of $M_{I,V} = -10$ and $M_{III,V} = -10$. Using the PAndAS data, we then measure the total luminosity of stars within 2.6 mags of the tip of the RGB and within one half-light radius from each of these galaxies, and compare this to the integrated luminosity measurement. We note that the 2.6 magnitude range corresponds directly to the limiting magnitude of $i = 23.5$ used in the creation of the star count map considering that the tip of the RGB of M33 is at $i = 20.9$ in the CFHT filter system. We find that we require a 2.016 and 2.05 magnitude offset for Andromeda I and III, respectively, to correct the RGB luminosity to the total luminosity (ie., this portion of the RGB is contributing 20 and 25% of the total light of these galaxies, which is reasonable for an old and metal poor population). Thus, to convert the stellar density distribution shown in Figure 11 to a surface brightness scale, we first measure the total luminosity of all the stars in each pixel of the stellar density map, and smooth the resulting map in the same way as before. We then correct this luminosity for stars outside of the metallicity cut used, where we derive the corrective factor from the metallicity distribution function in the lower panel of Figure 9 (our metallicity cut accounts for only 60% of the total number of stars/light in the substructure). Finally, we correct for the unresolved light component as calculated from Andromeda I and III. The final conversion of the contour levels in Figure 11 to surface brightness levels is given in Table 1. Implicit in these transformations is that the stellar populations of the substructure are identical to those for Andromeda I or III. Clearly, we do not expect this to be correct, but the small differences between the conversions for these galaxies implies that it is a reasonable approximation to make in the absence of more detailed information.

3.4.3. 1-D surface brightness profiles

Figure 12 shows the 1-D radial surface brightness profile (left panel) and azimuthal surface brightness profile (right panel) of the substructure. May be useful for modellers to fit to.

3.4.4. Integrated light

Overall luminosity of component in excess of $-12.7$. This means stellar mass is $>10^7 \text{Msuns}$. Dwarf galaxy regime. Also, if M33 has about 10th mass of M31, then $A \approx 0.5 \text{Gyr}$.
The diffuse filament toward M31 claimed by Braun & Thilker (2004) has an extent of 1–3 kpc, velocity widths of 17–30 km s$^{-1}$, and is located at the distance of M33. If located at the distance of M33 and are further from M33 (6–19 kpc from M33's H$^{-1}$). The heavy kinematic and spatial smoothing used in Braun & Thilker (2004) may have blended parts of the Galactic emission contrast from 0–15 K on a log scale. Velocity extends along the bottom axis and density contours from Figure 5.

The orbital history of M33 can be constrained by integrating the motion of M33 backward in time through M31's evolving gravitational potential. Since the proper motion of M33 has been recently measured (190 km s$^{-1}$), the only unknown velocity components are the tangential velocities of M31, ranging each between 10$^3$ and 10$^4$ km s$^{-1}$, and masses on the order of 10$^9$ solar masses. Of these seven, objects 1, 3, and 7 are in a noisier part of the cube and as can be seen from Figure 4, No. 2, 2009 DISRUPTION AND FUELING OF M33 1493, object 12 to the southern cloud. The other three objects (13, 14, and 15) are at velocities between -200 and -500 km s$^{-1}$ and have an angular extent of 1–3 kpc, velocity widths of 17–30 km s$^{-1}$, and are almost certainly associated with Wright's cloud. Object 5 appears spatially removed from Wright's cloud and could be considered part of object 2, or the main part of Wright's cloud. Object 9 is clearly related to the northern arc of M33.

Seven objects have central LSR velocities between +32 and +350 km s$^{-1}$; therefore including some Galactic emission to overlaid. Some of the scanning artifacts from drift scans are more evident in this map. The drift scans are more evident in this map. The heavy kinematic and spatial smoothing used in Braun & Thilker (2004) may have blended parts of the Galactic emission contrast from 0–15 K on a log scale. Velocity extends along the bottom axis and density contours from Figure 5.

The density contours from Figure 5 include the drift scans are more evident in this map. The drift scans are more evident in this map. The heavy kinematic and spatial smoothing used in Braun & Thilker (2004) may have blended parts of the Galactic emission contrast from 0–15 K on a log scale. Velocity extends along the bottom axis and density contours from Figure 5.
M33 Interaction seems plausible but is the model unique?

How can this interaction constrain the structure and dynamics of the Local Group?

We perform a Bayesian analysis of possible M33 orbits assuming different M31 potentials and M33 orbital parameters constrained by observations.
Consider different M31 potentials with varying mass and halo extent.
Local Group Data
(Priors)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{M31}$</td>
<td>785 kpc</td>
<td>+/- 25 kpc</td>
</tr>
<tr>
<td>$D_{M33}$</td>
<td>809 kpc</td>
<td>McConnachie TRGB distances</td>
</tr>
<tr>
<td>$v_{r,M31,helio}$</td>
<td>-301 km/s</td>
<td>+/- 1 km/s</td>
</tr>
<tr>
<td>$v_{r,M33,helio}$</td>
<td>-179 km/s</td>
<td>+/- 15 km/s</td>
</tr>
<tr>
<td>$v_{r,M31,G}$</td>
<td>-115 km/s</td>
<td>LSR uncertainty</td>
</tr>
<tr>
<td>$v_{r,M33,G}$</td>
<td>-42 km/s</td>
<td>+/- 50 km/s</td>
</tr>
<tr>
<td>$v_{\alpha,M33}$</td>
<td>-70 km/s</td>
<td>Brunthaler et al. 2005</td>
</tr>
<tr>
<td>$v_{\delta,M33}$</td>
<td>140 km/s</td>
<td></td>
</tr>
<tr>
<td>$v_{\alpha,M31}$</td>
<td>?</td>
<td>In this analysis, these are posteriors but now there is a measurement</td>
</tr>
<tr>
<td>$v_{\delta,M31}$</td>
<td>?</td>
<td></td>
</tr>
</tbody>
</table>
Relative Orbital Velocity in terms of galactocentric transverse and radial velocity components of M31 and M33

\[ \mathbf{v}_f = \mathbf{v}_{M33} - \mathbf{v}_{M31} \]  

(M33 orbital velocity wrt M31 now)

\[ T_A \] - rotation matrix from M33 to M31 tangent plane coordinates

\[ v_{f,x} = T_{A,11} v_{\alpha,M33} + T_{A,21} v_{\delta,M33} + T_{A,13} v_r,M33 - v_{\alpha,M31} \]

\[ v_{f,y} = T_{A,21} v_{\alpha,M33} + T_{A,22} v_{\delta,M33} + T_{A,23} v_r,M33 - v_{\delta,M31} \]

\[ v_{f,z} = T_{A,31} v_{\alpha,M33} + T_{A,32} v_{\delta,M33} + T_{A,33} v_r,M33 - v_r,M31 \]

\[ \chi^2 = \left( v_{f,z,obs} - v_{f,z,orbit} \right)^2 / \sigma_v^2 \]

\[ L \propto e^{-\chi^2 / 2} \]
Likelihood Function Involves the $z$ component of final orbital velocity in M31 tangent plane coordinates

$$\mathbf{v}_f = \mathbf{v}_{M33} - \mathbf{v}_{M31}$$  \hspace{1cm} (relative velocity)

$T_A$ - rotation matrix from M33 to M31 tangent plane coordinates

$$v_{f,x} = T_{A,11} v_{\alpha,M33} + T_{A,21} v_{\delta,M33} + T_{A,13} v_{r,M33} - v_{\alpha,M31}$$

$$v_{f,y} = T_{A,21} v_{\alpha,M33} + T_{A,22} v_{\delta,M33} + T_{A,23} v_{r,M33} - v_{\delta,M31}$$

$$v_{f,z} = T_{A,31} v_{\alpha,M33} + T_{A,32} v_{\delta,M33} + T_{A,33} v_{r,M33} - v_{r,M31}$$

$$\chi^2 = (v_{f,z,obs} - v_{f,z,orbit})^2 / \sigma_v^2$$

$$L \propto e^{-\chi^2/2}$$
Derive a marginal posterior pdf for M31 transverse velocities

\[
\begin{align*}
v_{f,x} &= T_{A,11}v_\alpha,M33 + T_{A,21}v_\delta,M33 + T_{A,13}v_r,M33 \\
&\quad - v_\alpha,M31 \\
v_{f,y} &= T_{A,21}v_\alpha,M33 + T_{A,22}v_\delta,M33 + T_{A,23}v_r,M33 \\
&\quad - v_\delta,M31 \\
v_{f,z} &= T_{A,31}v_\alpha,M33 + T_{A,32}v_\delta,M33 + T_{A,33}v_r,M33 \\
&\quad - v_r,M31
\end{align*}
\]

For a given orbit, solve for M31 transverse components and use its derived Bayesian probability to determine a pdf
The Importance of Dynamical Friction

Compute orbits in M31 potential that are consistent with Local Group priors - must include Chandra friction calibrated to N-body simulations
Likely M33 orbits for the case:

\[ t_{peri} < 4 \text{ Gyr} \]

\[ 30 \text{ kpc} < r_{peri} < 60 \text{ kpc} \]

M33 initially falls from behind M31 towards us

Apocentre \( \sim 200-400 \text{ kpc} \)

M33 is currently falling towards M31 - collision within \(< 1 \text{ Gyr} \)
Increasing M31 Halo Mass and Extent

Expected M31 Galactocentric Transverse Velocity $30 < r_p < 60$ kpc

"Predicted" proper motion for M31

pdf Contours: 10% 50% 95% 99%

Tuesday, June 26, 2012
Expected M31 Galactocentric Transverse Velocity
Increasing M31 Halo Mass and Extent

“Predicted” heliocentric proper motion for M31 (adjust for Sun’s motion)

Sohn, Anderson & van der Marel 2012
Increasing M31 Halo Mass and Extent

M33 apocentre

A starburst event occurred 2.6 Gyr ago in M31 outer warp (Bernard et al. 2012)!

Time since M33 pericentre passage
Local Group evolution as viewed from Sun’s current position fixed in inertial space 785 kpc from M31 - grazing collision

The Milky Way recedes into the distance towards encounter with M31+M33 and merger and transformation into an elliptical.