The Dark Matter and Satellites in the Milky Way and its Twins

NYU
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What is the formation history of the Milky Way?

Can we understand the population of satellites in the Milky Way?

What is the distribution of dark matter and its speeds in the Milky Way?

Is the Milky Way a typical galaxy?
How Common are the Magellanic Clouds?
— Lulu Lui, Brian Gerke, RW, Peter Behroozi, Michael Busha
  astro-ph next week

How Common are the Magellanic Clouds in Simulations?
— Busha, RW, Behroozi, astro-ph next week

What can the Magellanic Clouds teach us about the Mass Distribution and Formation History of the Milky Way?
— Busha, Phil Marshall, RW, Anatoly Klypin, astro-ph next week

The Dark Matter at the End of the Galaxy (a new model for velocity distributions for dark matter halos and implications for direct detection)
the LMC and SMC
The Missing Satellites problem is well known for low-mass objects, but what do we know about the high-mass end?

Only recently can we answer this question with decent statistics. Deep, wide-field surveys, medium-high resolution cosmological simulations, and statistical methods have been used to address this problem.

Fig. 5.—Cumulative number of Milky Way subhalos within $r_{200}$ (solid curve) and Milky Way satellites within 420 kpc (filled squares), as a function of circular velocity. The data points are from Mateo (1998), Simon & Geha (2007), and Martin et al. (2007), and assume a maximum circular velocity of $V_{\text{max}} = \sqrt{3}\sigma$ (Klypin et al. 1999). The short-dashed curve connecting the empty squares shows the expected abundance of luminous satellites after correcting for the sky coverage of the SDSS. The dash-dotted curve and long-dashed curve show the circular velocity distribution for the 65 largest $V_{\text{max}}$, $p_{\text{subhalo}}$ subhalos before accretion (LBA sample) and the "fossil of reionization" EF sample, respectively. This includes the 61 largest (sub)halos at $z = 13.6$. Therefore a solution to the substructure problem in which only the largest 50-100 $V_{\text{max}}$, $p_{\text{subhalo}}$ subhalos at all epochs were able to form stars efficiently would automatically place the luminous Milky Way dwarfs in the most massive subhalos at the present epoch.

To match the circular velocity function of the LBA sample, however, the observed dwarf spheroidals (dSphs) must have circular velocity profiles that peak at values well in excess of the stellar velocity dispersion (see Fig. 5 and discussion below). Note that the cut in $V_{\text{max}}$, $p_{\text{subhalo}}$ of the LBA sample requires star formation to be inhibited in all subhalos with $V_{\text{max}}$, $p_{\text{subhalo}} < 21\, \text{km s}^{-1}$, or virial temperature $T_{\text{vir}} = \mu\,m\,V_{\text{max}}^2 > 17,000$ K.

4. Suppressing Dwarf Galaxy Formation

The two thresholds for efficient star formation given in equations (5) and (6) provide the correct total number of luminous Milky Way satellites (assumed to be around 60-70), not a match to the observed circular velocity function. A careful look at Figure 5 suggests two possible solutions to the mismatch problem:

1. stars in the Milky Way dSphs are deeply embedded within their dark matter halos. The halo circular velocity profiles peak well beyond the luminous radius at speeds significantly higher than expected from the stellar line-of-sight velocity dispersion, i.e. $V_{\text{max}} \sim 3\sigma$ as suggested by Stoehr et al. (2002) and Peñarrubia et al. (2007). This scenario would shift the data points in Figure 5 by about a factor $\sqrt{3}$ further to the right, making the mass distribution of the luminous Milky Way dwarf spheroidals agree.

Note that the same is not true for the top 10 LBA subhalos (Kravtsov et al. 2004; Diemand et al. 2007b; Strigari et al. 2007a), as the largest $V_{\text{max}}$, $p_{\text{subhalo}}$ systems suffer the largest mass loss and are removed from the top ten list of more massive systems at $z = 0$. (6)
### Properties of the MW and its satellites

<table>
<thead>
<tr>
<th></th>
<th>$M_v$</th>
<th>$V_{\text{max}}$ [km/s]</th>
<th>$M_{\text{vir}}$ [M$_\odot$/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milky Way</td>
<td>-20.9</td>
<td>180-230$^a$</td>
<td>1-2×10^{12}$^{bc}$</td>
</tr>
<tr>
<td>LMC</td>
<td>-18.5</td>
<td>65$^d$</td>
<td>$\sim10^{10}$</td>
</tr>
<tr>
<td>SMC</td>
<td>-17.1</td>
<td>$\sim60^e$</td>
<td>$\sim10^{10}$</td>
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Searching for MC-like satellites around MW-like halos in the SDSS

- **MW-luminosity hosts:**
  - selected from SDSS DR7 spectroscopic sample with $m_r = 12-17$
  - $M_r = -21.2 \pm 0.2$
  - 22,581 hosts with MW luminosities
  - volume probed $\sim 240 \, (\text{Mpc}/h)^3$
  - isolated by $R_{\text{iso}} = 0.5 \, \text{Mpc}$ w/in 1000 km/s

- **MC-luminosity satellites:**
  - selected from SDSS DR7 photometric sample with $m_r < 21$, $z_{\text{phot}} < 0.23$
  - 2-4 mags dimmer than hosts
  - galaxies within 150 kpc projected around host
Biggest issue is background subtraction

First make cut in photo-z

Then statistically correct for background galaxies.

The galaxies around halos are correlated (correlation length ~ 3 Mpc)

Compare 2 results: random background and correlated background
Pause to emphasize a (obvious?) point:

- Correlated structures are a real issue when trying to calculate these probabilities in observations in general -- whether using photometry of spectroscopy.

- The velocity dispersion of a $10^{12} \text{M}_\odot/\text{h}$ halo is roughly 300 km/s, about 3 Mpc/h at $z = 0.1$. *This is well outside the virial radius of the halo.* A background subtraction is always necessary if you want the systems within a halo, even with spectroscopic information.
Number of Satellites vs. Probability

- Northern Galactic Cap
- Stripe 82
- Spectroscopic Set
How many Magellanic Cloud like satellites in simulations?

Bolshoi simulation (Klypin et al 2010)

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<table>
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<tbody>
<tr>
<td>Box size</td>
<td>250 Mpc/h</td>
</tr>
<tr>
<td># of Particles</td>
<td>2048$^{3}$</td>
</tr>
<tr>
<td>Mass Resolution</td>
<td>$1.35 \times 10^8 M_\odot$</td>
</tr>
<tr>
<td>Force Resolution</td>
<td>1 kpc/h</td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>0.27</td>
</tr>
<tr>
<td>$\Omega_\Lambda$</td>
<td>0.73</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>0.82</td>
</tr>
<tr>
<td>$n$</td>
<td>0.951</td>
</tr>
</tbody>
</table>

complete to $v_{max} = 50$ km/s

$\sim 30,000 \ 10^{12}$ Msun halos
Assigning luminosities to subhalos

assign luminosities to halos and subhalos using “subhalo abundance matching” (e.g. Kravtsov et al 04; Conroy, RW, Kravtsov 06; Behroozi, RW & Conroy 10)

note that volume probed by sims & data is similar. (sims give 5000 sq. degrees to z=0.09)
Results

excellent agreement!
slight differences but within systematic errors.
What can the MCs teach us about the MW?

- Typical approach: do some impressive measurements. Use a necessarily simplified dynamical model to interpret them.

- Our approach: Start with simple measurements. Use a large cosmological simulation which properly models the dynamics of large numbers of sample halos in their full cosmological context.
**What can the MCs teach us about the MW?**

- Observational Constraints on the Milky Way
  - Not a “satellite” of a larger structure
  - Has exactly two satellites clouds with $v_{\text{max}} > 55$ km/s
  - No other substructures within 300 kpc with $v_{\text{max}} > 25$ km/s

  Sagitarius is next brightest with $v_{\text{max}} \sim 20$ km/s ([Strigari et al 10](#))

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<thead>
<tr>
<th></th>
<th>LMC</th>
<th>SMC</th>
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<tbody>
<tr>
<td>$v_{\text{max}}$</td>
<td>~65 km/s</td>
<td>~60 km/s</td>
</tr>
<tr>
<td>$r_0$</td>
<td>50 kpc</td>
<td>60 kpc</td>
</tr>
<tr>
<td>$v_{\text{rad}}$</td>
<td>$89 \pm 4$ km/s</td>
<td>$23 \pm 7$ km/s</td>
</tr>
<tr>
<td>Speed</td>
<td>$378 \pm 18$ km/s</td>
<td>$301 \pm 52$ km/s</td>
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Watkins, Evans, & An 2010; Kallivayalil, van der Marel, & Alcock 06; Krachentsev et al 04; van der Marel et al 02
The Resulting Hosts

- Good matches are very rare!
  - only one 1 sigma halo per ~ 350 Mpc/h^3
  - need to sample multiple timesteps to get decent statistics.

One of the halos that’s a “good” match to the LMC/SMC system.
The Mass of the MW from the properties of its satellites
How does this compare to other methods?

- Battaglia 05: Radial velocity dispersion profile from globular clusters and satellites
- Smith 07: Escape velocity assuming NFW profile
- Xue 08: Radial velocity dispersion from BHB stars in SDSS
- Li 08: Timing Argument
Speculation that the Magellanic Clouds may have accreted as a bound object (e.g. Kallivaylil et al 06, D’Onghia & Lake 08).

The Bolshoi hosts that have similar $r_0$ and $r_v$ distributions strongly agree with this, halos with just $v_{\text{max}}$ selected LMC and SMC analogs don’t.

see also Boylan-Kolchin, Besla & Hernquist 2010
Lots more to do with this basic approach!

— Apply more priors to better constrain the mass (at the expense of statistics).

— Look at the posterior distribution of other properties and compare with observations, learn more about the MW.
What about the velocity distribution of the MW?

Average scattering rate depends on dark matter velocity distribution

\[
\frac{dR}{dE_R} = n_{dm} \left\langle \nu \frac{d\sigma}{dE_R} \right\rangle \text{ average over initial DM velocities}
\]

\[
\propto \int d^3\nu \frac{d\sigma}{dE_R} \nu f(\nu)
\]

Understanding the dark matter halo is critical for making predictions for direct detection experiments.
What about velocity distribution of the MW?

Density and velocity distribution fundamentally related through gravitational potential

\[ \rho(r) \rightarrow \rho(\psi) \rightarrow f(\psi, v) \]

\[ \nabla^2 \psi = -4\pi G \rho \quad \rho(\psi) = 4\pi \int dv \ v^2 f(\psi, v) \]

Must choose \( \rho(r) \) and \( f(v) \) distributions that are self-consistent
Velocity Distribution

(typical assumption)

Isothermal, isotropic Maxwell-Boltzmann distribution

\[ f_{\text{shm}}(v) \propto e^{v^2/v_0^2} \Theta(v_{\text{esc}} - v) \]

Drukier, Freese, & Spergel (1986).

"Standard Halo Model" does not exhibit double-power law behavior

\[ \rho_{\text{shm}}(r) \propto r^{-2} \]
Velocity Distribution

Phase space information can be obtained from N-body simulations

Maxwell-Boltzmann distribution is not a good fit

Living on the Tail
Overpredicts events at high velocities
Unphysical cutoff

Fairbairn and Schwetz (2009).
Basic idea

- We know that cosmological simulations predict a double power law.
- It turns out that only the outer slope matters for the high velocity particles.
- For isotropic equilibrium halos, there is a simple correspondence between the outer slope of the density profile.
Ansatz

\[ f(v) \propto \left( e^{-\left(\frac{v_{\text{esc}}^2 - v^2}{v_0^2} - 1\right)} \right)^{\gamma-3/2} \]

\( v \ll v_{\text{esc}} \) well described by a Gaussian peaked near \( v_0 \)

\( v \rightarrow v_{\text{esc}} \) distribution function approaches \( (v_{\text{esc}} - v)^k \)

Fewer events at higher energies than typical models used in the literature

\( \text{SHM} \quad k \rightarrow 0 \)

\( \text{King} \quad k = 1 \)
N-Body simulations

Check #2

$\frac{v^2 f(v)}{10^{-3}}$

$v (\text{km/s})$

Aquarius
$v_{\text{esc}} \sim 565 \text{ km/s}$

 Via Lactea
$v_{\text{esc}} \sim 550 \text{ km/s}$

SHM

$1.5 < k < 3.5$

$k = 1$
Scattering Rate

Scattering rate depends on the velocity distribution

\[ g_k(v_{\text{min}}) = \int_{v_{\text{min}}}^{v_{\text{esc}}} dv \ v f_k(\vec{v} + \vec{v}_E(t)) \]

threshold scattering velocity

For low \( v_{\text{min}} \), small differences between rates for different \( k \)
Scattering Rate

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threshold scattering velocity

For low \( v_{\text{min}} \), small differences between rates for different \( k \)

Rates for large \( v_{\text{min}} \) are significantly affected
For large scattering thresholds, the suppression can be several orders of magnitude.

$g_k/g_{k=1}$

$v_{\text{min}}/v_{\text{esc}}$

$v_0 = 220 \text{ km/s}$

$v_{\text{esc}} = 550 \text{ km/s}$
Minimum Velocity

The minimum velocity depends on the scattering kinematics

\[ v_{\text{min}} = \frac{1}{\sqrt{2m_N E_R}} \left( \frac{m_N E_R}{\mu_N} + \delta \right) \]

Will be large for the following scenarios:

**Theory**
- Inelastic dark matter
- Light elastic dark matter

**Experiment**
- Heavy nuclear target
- Large energy threshold
Changes in Rate

Each experiment is uniquely affected by change in velocity distribution

$$R_k$$ is scattering rate corresponding to $$f_k(v)$$

Significant effect for low mass dark matter

Heavy target, factor of 6 suppression
Changes in Rate

Each experiment is uniquely affected by change in velocity distribution

\[ R_k \text{ is scattering rate corresponding to } f_k(v) \]

Significant effect for low mass dark matter

Same target, different threshold factor of 25 suppression
Simulations and observations can estimate the probability of the Milky Way to host an LMC and SMC-like halos to excellent agreement.

- \( P(\text{LMC}) \sim 15\% \)
- \( P(\text{SMC}) \sim 5\% \)

Full \( P(N) \) for bright satellites is well predicted by LCDM -- no evidence for any sort of “missing” or “excess” substructure problem at the massive end of the satellite population.

We can constrain the mass distribution and formation history of the Milky Way using the properties of the Magellanic Clouds.

- \( M_{\text{MW}} = 1.45 \times 10^{12} \pm 0.4 M_\odot \), consistent with detailed kinematic studies of the MW.
- Predict recent, simultaneous accretion of the LMC and SMC.
- Favor a model for the MW halo with slightly lower concentration.

New analytic form for the velocity distribution for realistic DM halos which is in good agreement with cosmological simulations.

- Predicts fewer high velocity events than Maxwell-Boltzmann distribution.
- Significant implications for direct dark matter detection.
- Currently investigating in simulations: what are the implications of the MW prior?