Identifying the satellites of the Magellanic Clouds

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Dwarfs come in many sizes...

The LMC and its satellite galaxies

- M33: $2.9 \times 10^9 \, M_{\odot}$
- LMC: $1.5 \times 10^9 \, M_{\odot}$
- Fornax: $2 \times 10^7 \, M_{\odot}$
- Boötes: $3 \times 10^4 \, M_{\odot}$
- Segue 2: $\sim 10^3 \, M_{\odot}$

Stellar Mass vs. DM content
In a similar way than the MW has satellites, dwarf halos have smaller subhalos orbiting in their gravitational potentials.
The subhalo mass function is independent of host mass

**LCDM substructure around dwarfs**

The subhalo mass function is independent of host mass

Dark matter

Yang et al. 2011

Halo mass function (Sales et al., 2013)

The LMC and its satellite galaxies
The subhalo mass function is independent of host mass

(Sales et al., 2013)

But need to reach fainter magnitudes to improve the constraints

Where to look?
LMC must have brought along several of its own dwarfs satellites!

See also D’Onghia & Lake 2008
Laura V. Sales

Associated pre-infall material follows a well-defined path on the sky due to recent infall of the LMC.

Subhalos follow closely the distribution of all dark matter particles.

LMC analog in the cosmic simulations Aquarius

(Sales et al., 2011)

first pericenter ($t_{\text{ip}}$)
Looking for the dwarfs of the LMC

The LMC debris preserves coherence in phase-space.

Can be used to reconstruct the dwarfs with a common infall with the LMC.
Looking for the dwarfs of the LMC

Two criteria:

1) The distance and radial velocity must agree with the portion of the debris in the same position of the sky than the dwarf of interest

2) The orbital poles of the dwarfs must cluster on the sky near that of the LMC

Carina & Fornax did not pass test #2 in 2011

(Sales et al., 2011)
Clues to the “Magellanic Galaxy” from Cosmological Simulations

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ABSTRACT

We use cosmological simulations from the Aquarius Project to study the orbital history of the Large Magellanic Cloud (LMC) and its potential association with other satellites of the Milky Way (MW). We search for dynamical analogs to the LMC and find a subhalo that matches the LMC position and velocity at either of its two most recent pericentric passages. This suggests that the LMC is not necessarily on its first approach to the MW, provided that the virial mass of the Milky Way is as high as that of the parent Aquarius halo, M_{vir} = 1.8 \times 10^{12} M_{\odot}. The simulation results yield specific predictions for the position and velocity of systems associated with the LMC prior to infall. If on first approach, most should be close to the LMC because the Galactic tidal field has not yet had enough time to disperse them. On second approach, list of potential associates increases substantially, because of the greater sky footprint and velocity range of LMC-associated debris. Interestingly, our analyses rule out an LMC association for Draco and Ursa Minor, two of the dwarf spheroidals suggested by Lynden-Bell & Lynden-Bell to form part of the "Magellanic Ghostly Stream". Our results also indicate that the direction of the orbital angular momentum is a powerful test of LMC association. This test, however, requires precise proper motions, which are unavailable for most MW satellites. Of the 4 satellites with published proper motions, only the Small Magellanic Cloud is clearly associated with the LMC. Taken at face value, the proper motions of Carina, Fornax and Sculptor rule them out as potential associates, but this conclusion should be revisited when better data become available. The dearth of satellites clearly associated with the Clouds might be solved by wide-field imaging surveys that target its surroundings, a region that may prove a fertile hunting ground for faint, previously unnoticed MW satellites.

(Sales et al., 2011)
New dwarfs in the Dark Energy Survey (DES)

+ Orbits from GAIA

Credits: Breddels & Helmi

Credits: Drlica-Wagner et al. 2015, Koposov et al. 2015
GAIA 6D information allows to study membership of the LMC group

Several ultra-faint dwarfs (Car2, Car3, Hyd1, Hor1) together with the SMC, Carina and Fornax are consistent with having been accreted as part of the LMC group

• Sales et al. 2011, 2017 • Kallivayalil, Sales et al. 2018 • Jahn, Sales, et al. 2019

See also, Jetthawa+ 2016, 2018, Pardy+ 2019, Erkal+ 2019
Does this agree with LCDM expectations?
The luminous and dark satellites of the LMC in the FIRE simulations

See next talk by Ethan Jahn!

Jahn, Sales, et al., 2019
The associations of Carina & (possibly) Fornax to the LMC suggest a massive virial mass for the LMC at infall, $M_{200} > 3 \times 10^{11} M_{\odot}$

**Implications I: the mass of the LMC halo**

- Important implications for the stellar halo of the MW
  (see Gurtina Besla’s talk later on the week)

- It might induce deviations on cold streams

- Many… many more associated dwarfs to be discovered!

**The LMC and its satellite galaxies**

**Moster et al. (2013)**

$M^{\text{LMC}} \sim 1.5 \times 10^9 M_{\odot}$
(McConnachie 2012)

$z = 0$
$z = 1$
$z = 2$
$z = 3$
$z = 4$
Implications II: the star formation history of LMC dwarfs

Has the environment of the LMC halo helped shape the SFH of its companions?

- Ultra-faint dwarfs quenched at earlier times. Most due to reionization, but some may have been affected by the LMC

- Classical LMC companions form stars until later, in agreement with SFH of Carina and Fornax

Satin, Sales et al., in-prep
Implications II: the star formation history of LMC dwarfs

Has the environment of the LMC halo helped shape the SFH of its companions?

Jahn, Sales et al., in-prep
Several ultra-faint dwarfs (Car2, Car3, Hyd1, Hor1) together with the SMC, Carina and Fornax are consistent with having been accreted as part of the LMC group. These might suggest a massive virial halo for the LMC, $M_{200} \geq 3 \times 10^{11} M_{\odot}$.

The LMC environment might have helped quenching some of the massive ultra-faints / low mass classical dwarfs. No impact on most ultra-faints (quenched by reionization).

Future: constrain the luminosity function of LMC-mass objects in the field. WFIRST may provide a possible avenue.