Limit on the LMC mass from a census of its satellites

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\textbf{ABSTRACT}
We study the orbits of dwarf galaxies in the combined presence of the Milky Way and LMC and find 6 dwarfs which were likely accreted with the LMC (Car 2, Car 3, Hor 1, Hyi 1, Phe 2, Ret 2), in addition to the SMC, representing strong evidence of dwarf galaxy group infall. This procedure depends on the gravitational pull of the LMC, allowing us to place a lower bound on the Cloud’s mass of $M_{\text{LMC}} > 1.24 \times 10^{11} M_\odot$ if we assume these are LMC satellites. This mass estimate is validated by applying the technique to a cosmological zoom-in simulation of a Milky Way-like galaxy with an LMC analogue where we find that while this lower bound may be overestimated, it will improve in the future with smaller observational errors. We apply this technique to dwarf galaxies lacking radial velocities and find that Eri 3 has a broad range of radial velocities for which it has a significant chance ($> 0.4$) of having been bound to the Cloud. We study the non-Magellanic classical satellites and find that Fornax has an appreciable probability of being an LMC satellite if the LMC is sufficiently massive, $\sim 2.5 \times 10^{11} M_\odot$. In addition, we explore how the orbits of Milky Way satellites change in the presence of the LMC and find a significant change for several objects. Finally, we find that the dwarf galaxies likely to be LMC satellites are slightly smaller than Milky Way satellites at a fixed luminosity, possibly due to the different tidal environments they have experienced.

\textbf{Key words:} Galaxy: kinematics and dynamics, Galaxy: evolution, galaxies: Magellanic Clouds

1 INTRODUCTION

The hierarchical structure formation paradigm states that the smallest objects collapse first, and then merge to create larger and larger systems (White & Rees 1978). A natural consequence of this is that galaxies like our own are surrounded by a plethora of dwarf satellites. In addition, it suggests that many of these dwarfs should themselves have formed by accreting less massive objects and thus may host their own, even smaller, galaxy companions.

The Magellanic Clouds have long been considered a possible example of group infall (e.g. Avner & King 1967; Lynden-Bell 1976) with tentative evidence of associated satellites (e.g. Lynden-Bell & Lynden-Bell 1975, D’Onghia & Lake 2008, Sales et al. 2011). Recently, the Dark Energy Survey (DES) has mapped out a large fraction of the Southern Galactic hemisphere which uncovered a plethora of dwarfs close to the LMC (e.g. Koposov et al. 2015a, Bechtol et al. 2015, Drlica-Wagner et al. 2015b). This is in stark contrast to their distribution in the Northern Galactic hemisphere where they show little clustering. Motivated by this difference, Jethwa, Erkal & Belokurov (2016) modelled the expected distribution of satellites that the LMC and SMC would bring to the Milky Way. Their models found an excess of satellites was expected near the Magellanic Clouds as well as along the past and future orbits of the LMC. Similary, Sales et al. (2017) used a cosmological simulation of a Milky Way-like halo with an LMC analogue to predict the location and kinematics of the LMC satellites.

Based on the exquisite proper motions from \textit{Gaia} DR2, Kallivayalil et al. (2018) investigated which of the known satellites belonged to the LMC. Their approach is based on comparing the cosmological simulation of the LMC’s infall from Sales et al. (2017) with the satellite population observed today. They found four satellites which were consistent with their criteria for the expected population of the LMC satellites. Given that this work was based on a single simulation, it is unclear how the results would change if, for example, the properties of the LMC or the Milky Way were altered.

In order to address this, this paper tackles the same problem with a different technique. Instead of forward modelling the LMC satellites to the present (as in, e.g. Jethwa, Erkal & Belokurov 2016, Sales et al. 2017, Kallivayalil et al. 2018), we will rewind the satellites from their present day positions and determine which satellites were originally bound to the LMC. This approach has several advantages. First, we can explore a large parameter space by varying the properties of the LMC. Second, we can determine what LMC mass is needed to bind each of the satellites in order to constrain the LMC mass. Third, this method can be used to estimate the orbit of each satellite relative to the Milky Way and the LMC. Finally, this independent technique provides a useful check of the results in Jethwa, Erkal & Belokurov (2016), Kallivayalil et al. (2018).

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This rewinding technique was originally used in Kallivayalil, van der Marel & Alcock (2006); Kallivayalil et al. (2013) in order to determine whether or not the LMC and SMC were accreted as a pair. It is also similar to the method presented in Price-Whelan et al. (2014). An important difference introduced here is that we also account for the motion of the Milky Way in response to the LMC’s infall. This effect was first highlighted in Gómez et al. (2015). Given the large LMC mass inferred from abundance matching (Behroozi, Wechsler & Conroy 2013; Moster, Naab & White 2013), the timing argument with Andromeda (Peharriba et al. 2016), and from its deflection of the Orphan stream (Erkal et al. 2019), this effect is essential to include.

This paper is organised as follows. In Section 2 we describe the rewinding method and then apply it to 32 ultra-faint dwarf galaxies and the classical satellites. Additionally, in order to test the technique, we apply it to a cosmological zoom-in simulation in Section 3. We discuss some implications of these results in Section 4, and then conclude in Section 5.

2 METHOD

2.1 Satellite properties

Gaia DR2 (Gaia Collaboration et al. 2018a) has delivered a plethora of data on the Milky Way. Shortly after the data release, a number of works measured the proper motions of dwarf galaxies around the Milky Way (Simon 2018; Fritz et al. 2018; Pace & Li 2019). Using these proper motions, combined with radial velocities measured from other studies, we have a sample of 25 ultra-faint dwarfs with 3d positions and 3d velocities (see Tab. A1). For the LMC properties, we use a distance of 49.97 ± 1.126 kpc (Pietrzyński et al. 2013), a radial velocity of 262.2 ± 3.4 km/s (van der Marel et al. 2002), and a proper motions of $\mu_x = 1.91 ± 0.02$ mas/yr, $\mu_y = 0.229 ± 0.047$ mas/yr (Kallivayalil et al. 2013).

In Figure 1 we show the relative position and velocity of these satellites with respect to the LMC. The curves show the escape velocity curve assuming different masses for the LMC. In each case, the LMC is treated as a Hernquist profile (Hernquist 1990) with a scale radius that the circular velocity at 8.7 kpc matches the observed value of 91.7 km/s (van der Marel & Kallivayalil 2014). Interestingly, this figure shows that there is a population of satellites which are close in both position and velocity to the LMC. We stress that we do not use the present day position in phase space to determine whether each satellite belongs to the LMC but rather rewind the satellites in time as described below.

In addition, there are 7 dwarfs which only have proper motions but no radial velocity measurements. For these dwarfs, we will sample over the possible radial velocities to determine whether there exist any radial velocity for which they could be associated with the LMC. Finally, we also repeat our analysis on the classical Milky Way satellites.

2.2 Probability of being an LMC satellite

In order to determine whether each satellite was originally associated with the LMC, we Monte Carlo sample its $6d$ phase space position by sampling the distance, radial velocity, and proper motion (including covariance) using (multivariate) Gaussian error distributions with means and standard deviations given by the values in Table A1. We similarly Monte Carlo the LMC’s $6d$ position and rewind the satellite and LMC for 5 Gyr. This rewinding is done in a Milky Way potential similar to MWPotential2014 from Bovy (2015). Namely, we model the dark matter halo as an NFW profile (Navarro, Frenk & White 1997) with a virial mass of $8 \times 10^{10} M_\odot$, a scale radius of 16 kpc, and a concentration of 15.3. We use a Miyamoto-Nagai disk (Miyamoto & Nagai 1975) with a mass of $6.8 \times 10^{10} M_\odot$, a scale radius of 3 kpc, and a scale height of 0.28 kpc. For the bulge we use a Hernquist profile with a mass of $5 \times 10^9 M_\odot$ and a scale radius of 0.5 kpc. This bulge has the same mass as the bulge in MWPotential2014 from Bovy (2015) but we have changed the profile for computational efficiency.

Once the satellite and LMC have been rewound, we compute the energy of the satellite relative to the LMC is then computed to determine whether the satellite was energetically bound. At this time, the LMC is typically quite distant from the Milky Way (~ 650 kpc for a $1.5 \times 10^{11} M_\odot$ LMC) and thus this also effectively selects satellites which were close to the LMC at this time. If the LMC reaches apocenter during the 5 Gyr interval, we stop the rewinding procedure and compute the energy at that time. This is motivated by the assumption that the LMC is on first approach to the Milky Way (e.g. Besla et al. 2007; Kallivayalil et al. 2013). We have tested that the probability that a satellite is associated with the LMC does not depend sensitively on this choice of integration time. We have repeated our analysis with rewinding times of 3 Gyr and 7 Gyr and found that the probabilities of being an LMC satellite change by ~ 3% on average.

This procedure is repeated 10,000 times for each satellite and LMC mass combination. During this rewinding, we include the dy-
namical friction of the Milky Way on the LMC using the prescription in [Jethwa, Erkal & Belokurov (2016)]. We also account for the motion of the Milky Way in response to the LMC which can move it a significant amount (e.g. Gomez et al. 2015, Erkal et al. 2019). We note that neither the LMC nor Milky Way tidally deform during their interaction but rather are treated as rigid potentials. Each dwarf is treated as a massless tracer under the combined influence of the Milky Way and LMC.

We consider a grid of LMC masses: 2, 5, 10, 15, 20, 25, 30 \times 10^{10} M_\odot. This lower limit is motivated by the mass constraint within 8.7 kpc from van der Marel & Kallivayalil (2014) and the upper limit is motivated by the LMC mass inferred in Peñarrubia et al. (2016) based on the nearby Hubble flow and the timing argument with Andromeda. The LMC is modelled as a Hernquist profile (Hernquist 1990) with a scale radius such that the circular velocity is 91.7 km/s at 8.7 kpc as observed by van der Marel & Kallivayalil (2014).

In Figure 2 we show the probability of being bound to the LMC as a function of the LMC’s mass. We find two distinct populations, one which shows a significant probability of being bound even for modest LMC masses. We postulate these to be LMC satellites. The second population shows a low chance of being bound at low LMC masses which increases with LMC mass but only reaches a modest probability even for the most massive LMC we consider. We conclude that these are the Milky Way satellites. Interestingly, some of the LMC satellites (Hor 1, Car 2, Car 3, and the SMC) have a non-zero probability of being bound even with the lowest LMC mass considered suggesting that these sit deep in the potential of the LMC. The binding probabilities for an LMC mass of 1.5 \times 10^{11} M_\odot (motivated by the results of Erkal et al. [2019]) are given in Table 1.

In order to determine how sensitive these results are to the uncertainty in the mass and profile of the Milky Way, we repeat the analysis with a 25% more massive Milky Way halo, 10^{12} M_\odot. Motivated by the Milky Way mass measurements from Erkal et al. (2019), we increase the Milky Way halo’s scale radius to 19 kpc to be consistent with their constraints. We note that this 25% change in the mass is larger than the 1\sigma uncertainty in the Milky Way mass from Erkal et al. (2019). Across all of the satellites, we find that the binding probabilities change by 1\% on average with a maximum change of 5\%. Thus, our results do not appear to be very sensitive to the mass of the Milky Way given current constraints.

### 2.3 Mass of the LMC

Next, we use the likely LMC satellites to estimate the mass of the Cloud. This is done by assuming that each of the 7 dwarfs with a significant chance of being bound is truly an LMC satellite. For each object, we make 10,000 Monte Carlo realizations of its orbital evolution in the presence of the LMC. For each realization, we begin with an LMC mass of 2 \times 10^{10} M_\odot and rewind the satellite and the LMC as described above to determine whether it is bound. If the satellite is not bound, we increase the LMC mass by 10^{10} M_\odot and repeat therewinding procedure. This is repeated until we find an LMC mass for which this particular realization of the satellite is bound. We call this the minimum mass needed to bind the satellite since it would also be bound for a more massive LMC. If the LMC mass exceeds 3 \times 10^{11} M_\odot, we classify the satellite as unbound and move onto the next realization. This process then yields a distribution of the minimum LMC mass needed to bind the satellite.

In Figure 3 we show the distribution of the minimum mass needed to bind the satellites considered. Of all the satellites, Phe 2 requires the highest LMC mass, 1.24 \times 10^{11} M_\odot. Although this mass is larger than what has been measured in the inner part of the LMC (van der Marel & Kallivayalil [2014]), it is significantly less than the mass measured using the Orphan stream (Erkal et al. [2019]) or the mass measured using the nearby Hubble flow and the timing argument with Andromeda (Peñarrubia et al. [2016]). Car 2 requires the lowest LMC mass in order to bind it, consistent with its high probability of being bound even for a low LMC mass (see Fig. 2). The median LMC mass needed to bind each satellite can be found in Table 1.

### 2.4 Satellites without radial velocities

This rewinding technique can also be used on satellites without radial velocities. In order to do this, we sample the proper motions and distance from their observed distributions, and uniformly sample the radial velocities over the range -500 to 500 km/s. For each satellite, we make 200,000 such samples and then bin the velocities with a width of 10 km/s. For each velocity bin, we compute the probability of being bound to a 1.5 \times 10^{11} M_\odot LMC, and then take the maximum probability across all of these bins. The results are shown in Table 1. For the satellites with a maximum probability above 0.4, we give the radial velocity range with this probability. We see that there exist radial velocities for which Eri 3 would have a high probability, 0.50, of being bound an LMC satellite. We note that some of these satellites have large proper motion errors (e.g. Hor 2 has errors of 0.42 mas/yr and 0.66 mas/yr) which will naturally lead to a low probability of membership even for genuine LMC’s companions. Thus, the membership probability for these satellites should be revisited once better proper motions are available.
figure 3. Distribution of minimum mass needed to bind the satellites to the LMC. We show the SMC and six ultra-faint satellites which have a significant chance of being bound. In each panel, the dashed-red vertical line shows the median LMC mass needed to bind the satellite. Phe 2 requires the highest LMC mass in order to bind it, \(12.4 \times 10^{10} M_\odot\).

### 2.5 Classical dwarfs

In order to assess whether any of the other classical dwarfs could have fallen in with the LMC, we repeat our analysis for them with an LMC mass of \(1.5 \times 10^{11} M_\odot\) and \(2.5 \times 10^{11} M_\odot\). The results are shown in Table 1. We find that for a \(1.5 \times 10^{11} M_\odot\) LMC, none of the classical satellites (excluding the SMC) have an appreciable probability of belonging to the LMC. Increasing the LMC mass to \(2.5 \times 10^{11} M_\odot\), we find that Fornax has the highest probability, 0.459, of having been bound to the LMC in the past. Interestingly, Figure 1 shows that Carina is closer to the LMC in phase space than Fornax. Despite this, Fornax has a significantly higher probability of being bound to the LMC. This shows that the present day binding energy can be misleading and one needs to either rework the satellites as done in this work, or model their stripping from the LMC (e.g. Jethwa, Erkal & Belokurov 2016 [Sales et al. 2017] [Kallivayalil et al. 2018]).

This analysis thus provides a useful counterpoint to those based on the orbital plane alignment of the classical satellites (e.g. Pardy et al. 2019) which have suggested that both Carina and Fornax may have originally been LMC satellites.

### 2.6 Globular clusters

In addition to dwarfs, we can also check if there are globular clusters which were accreted along with the LMC. We repeat the same analysis using the coproduct of globular clusters with 3d positions and velocities from Vasiliu (2019). Note that this catalogue does not include the 16 currently known globular clusters (e.g. Georgiev et al. 2010) which were unambiguously associated to the LMC due to their proximity. We find that none of the globular clusters considered are consistent with an LMC origin, and the cluster with the highest probability of membership is Pal 14 which has a modest probability, 0.135 (for an LMC mass of \(1.5 \times 10^{11} M_\odot\)). It is unclear whether this lack of additional globular clusters is surprising since the LMC already falls within the scatter of the virial mass-globular cluster mass relation (e.g. Forbes et al. 2018). However, this scatter is quite large for galaxies in the mass range of the LMC, thus indicating that there could be additional globular clusters. Furthermore, it is possible that some of the ultra-faint dwarfs which we find to be LMC satellites are in fact globular clusters (e.g. Car 3, Torrealba et al. 2018).

### 3 TESTING WITH A COSMOLOGICAL SIMULATION

In this section we test this method of identifying LMC group members in a cosmological zoom-in simulation of a Milky Way-like halo with an LMC analogue at the present. This simulation is described in Jethwa, Erkal & Belokurov (2018) and is evolved with the N-body part of gadget-3 which is an updated version of gadget-2 (Springel 2005).

In order to compare with the LMC, we choose the snapshot shortly after the pericenter of the LMC analogue. This occurs at a scale factor of 0.96 which corresponds to a lookback time of 0.5 Gyr. At this time, the Milky Way-analogue has a virial mass of \(8.77 \times 10^{11} M_\odot\), a scale radius of 20.5 kpc, and a concentration of 12.1. In the rewinding procedure, we use these values for the Milky Way potential at all times. At the same scale factor, the LMC analogue has a mass of \(7.01 \times 10^{10} M_\odot\) and a peak mass of \(7.96 \times 10^{10} M_\odot\). For consistency, we treat the LMC as a Hernquist profile which matches the circular velocity, 69 km/s, of the LMC-analogue at a given radius which we choose to be 5 kpc.

We select the 20 closest satellites to the LMC in distance. 14 of these were originally LMC satellites given that they were within the LMC’s virial radius before the LMC was accreted onto the Milky Way. For each satellite, we make mock observations from the location of the Sun. We include an error in the distance (6.4% distance error), radial velocity (1.15 km/s), and proper motions (0.1015, 0.098 mas/yr in \(\mu_\alpha, \mu_\delta\) respectively) based on the median errors in our sample of dwarfs. This is also done for the LMC-analogue with errors from the LMC observations in the literature.

The position and velocity of these satellites relative to the LMC is shown in Figure 4. For reference, the escape velocity curves of the LMC-analogue given its peak mass (present-day mass) is shown as a solid-black (dashed-black) line. Interestingly, many of the LMC satellites are energetically unbound at the present day. This difference is due to the tidal field of the Milky Way-analogue. This highlights the fact that using the present-day escape velocity could lead us to miss a large fraction of the LMC satellites.

Given the mock observations made of these satellites, the approach is identical to what is described in Section 2. First, we calculate the probability of being bound to the LMC-analogue as a function of its mass and then compute the distribution of masses needed to bind each satellite. As a test of the method, we compute the probability of being bound to the LMC-analogue using the peak mass of the LMC (7.96 \times 10^{11} M_\odot) and encircle these with a red, green ring in Figure 4 if the probability is greater than 0.5, 0.4, 0.3 respectively. For these probability thresholds, we recover 7, 12, 13 out of 14 LMC satellites respectively. This figure shows that the method presented in this work can distinguish between Milky Way and LMC satellites close to the LMC with a high fidelity. Indeed, the Milky Way satellite with the highest chance of belonging to the LMC only has a 28.5% chance of being an LMC satellite. As expected, the technique performs better for satellites closer to the LMC in phase space, but it is also capable of correctly classifying LMC satellites which are unbound at the present.

We note that the technique fails for the most distant mock LMC satellite. As expected, the technique performs better for satellites closer to the LMC in phase space, but it is also capable of correctly classifying LMC satellites which are unbound at the present. Since we are using a fixed uncertainty in the mock observables, this makes sense since the most distant satellite from the LMC will have the most uncertainty in its orbit. In order to check this, we repeated...
Satellite census and LMC mass

| Likely LMC satellites | $p_{\text{LMC}}(1.5 \times 10^{11} M_\odot)$ | $M_{\text{LMC}}(10^{10} M_\odot)$ |
|-----------------------|---------------------------------|----------------------------------|
| Car 2                | 0.972                           | 2.0                              |
| Car 3                | 1.0                             | 2.4                              |
| Hor 1                | 0.753                           | 5.8                              |
| Hyi 1                | 0.996                           | 5.1                              |
| Phe 2                | 0.532                           | 12.4                             |
| Ret 2                | 0.643                           | 9.5                              |
| SMC                  | 0.785                           | 7.7                              |
| Ant 2                | 0.030                           | 0.148                            |
| Aqu 2                | 0.012                           | 0.042                            |
| Boo 1                | < 0.0001                        | < 0.0001                         |
| Boo 2                | 0.0007                          | 0.045                            |
| Com                  | < 0.0001                        | 0.007                            |
| Cra 2                | 0.007                           | 0.149                            |
| Dra 2                | 0.015                           | 0.034                            |
| Eri 2                | 0.001                           | 0.002                            |
| Gru 1                | 0.017                           | 0.079                            |
| Her 1                | 0.014                           | 0.092                            |
| Hya 2                | 0.045                           | 0.121                            |
| Seg 1                | 0.016                           | 0.048                            |
| Seg 2                | < 0.0001                        | < 0.0001                         |
| Tri 2                | 0.006                           | 0.064                            |
| Tuc 2                | 0.124                           | 0.179                            |
| Tuc 3                | 0.078                           | 0.217                            |
| UMa 1                | < 0.0001                        | < 0.0001                         |
| UMa 2                | 0.0007                          | 0.002                            |
| Wil 1                | < 0.0001                        | 0.0004                           |
| Carina               | 0.004                           | 0.125                            |
| Draco                | 0.087                           | 0.090                            |
| Fornax               | 0.128                           | 0.449                            |
| Leo 1                | 0.132                           | 0.181                            |
| Leo 2                | 0.073                           | 0.232                            |
| Sagittarius          | 0.002                           | 0.031                            |
| Sculptor             | < 0.0001                        | 0.281                            |
| Sextans              | < 0.0001                        | 0.034                            |
| Ursa Minor           | 0.002                           | 0.096                            |

| Bottom table | $p_{\text{LMC}}(1.5 \times 10^{11} M_\odot)$ | $p_{\text{LMC}}(2.5 \times 10^{11} M_\odot)$ |
|--------------|---------------------------------|----------------------------------|
| Carina       | 0.004                           | 0.125                            |
| Draco        | 0.087                           | 0.090                            |
| Fornax       | 0.128                           | 0.449                            |
| Leo 1        | 0.132                           | 0.181                            |
| Leo 2        | 0.073                           | 0.232                            |
| Sagittarius  | 0.002                           | 0.031                            |
| Sculptor     | < 0.0001                        | 0.281                            |
| Sextans      | < 0.0001                        | 0.034                            |
| Ursa Minor   | 0.002                           | 0.096                            |

Satellites with missing radial velocity

| Satellite | $\text{max}(p_{\text{LMC}})$ | $v_r$ with $p_{\text{LMC}} > 0.4$ |
|-----------|-------------------------------|-----------------------------------|
| Col 1     | 0.054                         | –                                 |
| Eri 3     | 0.50                          | [50,200] km/s                     |
| Gru 2     | 0.15                          | –                                 |
| Hor 2     | 0.20                          | –                                 |
| Pic 1     | 0.18                          | –                                 |
| Ret 3     | 0.0005                        | –                                 |
| Tuc 4     | 0.28                          | –                                 |

Table 1. Summary of results in this study. Top table shows the likely satellites of the LMC. The second column shows the probability of having been bound to the LMC assuming at LMC mass of $1.5 \times 10^{11} M_\odot$. The third column shows the median LMC mass needed to bind each satellite. Middle table shows satellites which have a low probability of being LMC satellites. For each satellite, we give the probability of having been bound to a $1.5 \times 10^{11} M_\odot$. Bottom table shows satellites which lack radial velocity information. The second column there shows the range of radial velocities for which the probability of being an LMC satellite is larger than 0.5 assuming an LMC mass of $1.5 \times 10^{11} M_\odot$. If the probability never rises above 0.5, the radial velocity is left blank.
shown in dotted-blue. We see that 6 out of 14 satellites of the LMC analogue have median binding masses larger than the peak mass of the LMC analogue. This shows that the LMC mass estimate in Section 2 may be overestimated. We note this mass estimate depends on the size of the observational errors of the dwarf properties. If the errors are large then a significant fraction of the realizations will be unbound when using the true mass of the LMC. Applying the same technique on the satellites of the Milky Way analogue gives significantly higher LMC masses since the Cloud must strip them from the Milky Way during the rewinding process.

Finally, our mock dwarf catalogue allows us to test how this satellite classification will look with reduced errors from the future observations. In order to assess this, we repeat the analysis assuming errors which are half as large in distance, radial velocity, and proper motion. With these reduced errors, the Milky Way satellite with the highest probability of being bound to the LMC given the LMC’s peak mass only has \( p_{\text{LMC}} = 0.097 \). Furthermore, all but 3 LMC satellites have \( p_{\text{LMC}} > 0.5 \). Thus, as the data quality improves in the future, this method will become more precise in distinguishing LMC satellites from those of the Milky Way. This will also improve the mass estimate of the LMC.

4 DISCUSSION

4.1 Comparison with previous works

After the discovery of the DES satellites, Deason et al. (2015) used cosmological simulations to explore the expected properties of LMC satellites. They used these results to assign each satellite a probability of being an LMC satellite based on their distance from the LMC. Interestingly, they assigned Ret 2 the highest probability and Hor 1 the third highest probability. Overall, they predicted that between 2 – 4 of the original 9 DES dwarfs were LMC satellites. This agrees with well our result that 3 of these satellites likely belong to the LMC (Ret 2, Hor 1, Phe 2) and that there exist radial velocities for which Eri 3 was originally bound to the LMC.

Yozin & Bekki (2015) also explored this association by rewinding satellites in the presence of the Milky Way, LMC, and SMC. They found that if the Magellanic Clouds were on first approach, the satellites of the LMC should inhabit a relatively small range of distances, in broad agreement with the distances of the DES satellites.

Without proper motions (and for many objects without the radial velocity), Jethwa, Erkal & Belokurov (2016) made predictions as to which dwarfs were accreted with the LMC. Of their 7 highest confidence candidates \( (p_{\text{LMC}} > 0.7) \), we confirm that Hor 1, Ret 2, and Phe 2 are likely LMC satellites. We also find that there are radial velocities for which Hor 2 and Tuc 4 have modest probabilities \((0.2, 0.28)\) respectively of being an LMC satellite. However, we find that Tuc 2 is very unlikely to be an LMC satellite. Among their 5 medium probability candidates \((0.5 < p_{\text{LMC}} < 0.7)\), we rule out Tuc 3 and Gru 1. The other 3 (Gru 2, Pic 1, Ret 3) are missing radial velocities although we note that the maximum probability of being bound for Ret 3 is 0.0015 and thus it is very unlikely to be an LMC satellite.

Similarly, Sales et al. (2017) predicted the properties of LMC satellites with known satellites and found that Hor 1 agreed with the properties known at that time (i.e. without proper motions). In addition, they found Hor 2, Eri 3, Ret 3, Tuc 4, Tuc 5, and Phe 2 had on-sky positions and distances consistent with a Magellanic origin. Of these, we confirm Phe 2 is likely an LMC satellite. We also find

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**Figure 4.** Relative position and velocity between the LMC analogue and dwarf galaxy analogue in our cosmological simulation. The solid line shows the escape velocity curve when the LMC-analogue achieved its peak mass and the dashed line shows the escape velocity curve at the present. The colored rings show the probability of having been bound when using the peak mass of the LMC. Interestingly, many of the LMC’s satellites are energetically unbound with respect to the LMC-analogue. Thus, using only the present-day position and velocity would lead to an overestimate of the LMC’s mass. We also see that this method does a good job separating the Milky Way satellite closest to the LMC. This satellite only has a 28.5% chance of belonging to the LMC despite appearing to be energetically bound.

**Figure 5.** Minimum mass needed to bind satellites to the LMC analogue in the cosmological simulation. The red histogram shows the median mass needed for LMC satellites while dashed-blue histogram shows the minimum mass needed for Milky Way satellites. The vertical dashed-black line shows the peak mass of the LMC in the simulation. While 8 of the true LMC satellites require a mass less than the LMC’s peak mass, 6 require a higher mass. Thus, with the current errors, it is possible that the LMC mass will be overestimated with this technique. Furthermore, if a Milky Way satellite is energetically unbound with respect to the LMC-analogue, this satellite only has a 5% chance of belonging to the LMC despite appearing to be energetically unbound.

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that there are radial velocities for which Eri 3 would likely be an LMC satellite. Their remaining satellites still do not have complete measurements of their kinematics. However, as mentioned above, we find Ret 3 is very unlikely to be an LMC satellite.

Finally, our results can also be compared with those of Kallivayalil et al. (2018). Using a different technique based on a single cosmological simulation, they identified Car 2, Car 3, Hor 1, and Hyi 1 as likely LMC satellites, in agreement with this work. They also identified Ret 2, Tuc 2, and Gru 1 as inconsistent with the LMC at the 3σ level in velocity. However, our analysis suggests that Ret 2 is likely to be a LMC satellite. This discrepancy may be due to the modest LMC mass of 3.6 × 10^10 M⊙ used in Kallivayalil et al. (2018). Furthermore, they suggest that Hya 2 and Dra 2 could be LMC satellites although these are essentially ruled out as LMC satellites in this work. Finally, they also argued that Phe 2 could be an LMC satellite based on their prediction of its proper motion and the existence of an overdensity of stars with that proper motion in Gaia DR2. Our analysis which makes use of the observed proper motion and radial velocity from Fritz et al. (2019) finds that Phe 2 is a likely LMC satellite.

### 4.2 Structural properties of dwarfs

Now that we can distinguish which satellites belong to the Milky Way and the LMC, we can contrast their structural properties. In Figure 6 we compare the half-light radius versus magnitude for objects with 6d data; here the LMC satellites are shown in red and the Milky Way satellites shown in black. At a fixed magnitude, the LMC satellites appear to be smaller. This could be a sign that the tidal radii of the LMC satellites are smaller since they orbit a less massive host compared to the Milky Way satellites. This is also interesting in the context of similar comparisons between Milky Way satellites and those of M31 where it was found that the M31 satellites were larger by a factor of 2 (McConnachie & Irwin 2006). However, a subsequent and more detailed analysis concluded that this difference was not statistically significant (Brasseur et al. 2011).

### 4.3 Satellite planes around the LMC

Jethwa, Erkal & Belokurov (2016) found 7 satellites (Gru 1, Gru 2, Phe 2, Tuc 2, Tuc 3, Tuc 4, Tuc 5) reside in a thin plane around the LMC. This is especially interesting given the planes of satellites around the Milky Way (e.g. Lynden-Bell (1976), Pawlowski, Pfannm-Altenburg & Kroupa (2012), Andromeda (Ibata et al. 2013), and Centaurus A (Müller et al. 2018). While they found this plane was significant, they also noted that their models showed that Gru 1, Gru 2, and Tuc 3 were likely to be MW satellites. From the results of this work, we confirm that Gru 1 and Tuc 3 are not associated with the LMC. Gru 2 is also not associated with the LMC since there is no radial velocity for which it has a significant LMC membership probability. Furthermore, we find that Tuc 2 is also not associated with the LMC. Of the remaining satellites, we confirm that Phe 2 is an LMC satellite, that Tuc 4 has a chance of being an LMC satellite. We did not investigate Tuc 5 due to the lack of proper motions. Therefore, at most 3 out of the original 7 satellites are associated with the LMC which makes the plane less significant.

In Figure 7 we show the on-sky distribution of satellites near the LMC along with their classification from this work using the Magellanic Stream coordinate system from Nidever, Majewski & Butler Burton (2008). While the plane from Jethwa, Erkal & Belokurov (2016) is now less significant, we find that the majority (5 out of 7) of the known LMC satellites do reside in a thin plane. In order to check whether the kinematics of these satellites are consistent with a long-lived plane, we show their proper motions of relative to the LMC. This is done by taking the 3d velocity of each satellite, subtracting the 3d velocity of the LMC, and computing the resulting proper motion as viewed from the Sun. Since many of the LMC satellites have substantial velocity components perpendicular to the plane, we conclude that the plane is likely a chance alignment.

### 4.4 Change to satellite orbits

Since we follow the orbits of the satellites over the past 5 Gyr, we can study how these change due to the inclusion of the LMC. This is particularly useful for understanding which satellites should be tidally affected by the Milky Way. For this comparison, we use the orbits computed in Section 2.3 for an LMC mass of 2.5 × 10^11 M⊙, as well as orbits computed without the influence of the LMC. For each satellite, we compute the median pericenter with respect to the Milky Way. In Table 2 we show the satellites whose median pericenters change by 25% or more. Note that in this search we ignore the 7 satellites we have associated with the LMC.

Interestingly, both Ant 2 and Cra 2 have significantly smaller pericenters in the presence of the LMC. Both of these satellites are quite diffuse and strong tidal disruption has been suggested as being responsible for this (e.g. Sanders, Evans & Dehnen (2018), Torrealba et al. 2019). This shows that it is crucial to model these systems in the presence of the LMC if we want to understand their genesis.

In order to assess the significance of this change to the satellite orbits, we find the orbits of these satellites in a 25% more massive Milky Way halo as in Section 2.2. This increase in Milky Way mass lowers the pericenters by an average of 4%, with a maximum change of 8% for Ant 2. This is much smaller change than the effect of including the LMC, suggesting that it is crucial to include the LMC for these satellites.
Figure 7. On-sky distribution of satellites around the LMC showing a possible plane of satellites. The distribution is shown in Magellanic Stream (MS) coordinates \cite{nidever2008}. The red triangle shows the LMC, the red circle shows the SMC, and the red squares show high probability LMC satellites identified in this work. The black circles show the satellites inconsistent with an LMC origin and the grey diamonds show satellites without radial velocities for which we did determine membership. Arrows show proper motions relative to the LMC as described in the text. The two satellites without radial velocities close to the plane are Tuc 4 and Gru 2.

| Satellite | Pericenter inc. LMC | Change to pericenter |
|-----------|---------------------|----------------------|
| Ant 2     | 25.7$^{+9.2}_{-5.7}$ kpc | 0.63 |
| Cra 2     | 19.7$^{+13.9}_{-12.8}$ kpc | 0.41 |
| Her 1     | 72.3$^{+15.8}_{-12.6}$ kpc | 1.25 |
| Tuc 3     | 21.1$^{+17.4}_{-10.4}$ kpc | 0.75 |
| Carina    | 73.3$^{+25.3}_{-10.2}$ kpc | 0.69 |
| Draco     | 73.1$^{+13.9}_{-10.6}$ kpc | 1.96 |
| Ursa Minor| 71.3$^{+23.9}_{-10.6}$ kpc | 1.66 |

Table 2. Change to pericenter of satellite orbit with respect to the Milky Way. The middle column gives the median pericenter, with 1σ scatter, of the satellite with respect to the Milky Way in the presence of a $2.5\times10^{11} M_\odot$ LMC. The third column shows the fractional change of this median pericenter from satellite orbits without the influence of the LMC.

4.5 Expected number of satellites around the LMC

Jethwa, Erkal & Belokurov (2016) predicted that the number of LMC satellites in the magnitude range $−7 < M_V < −1$ was 70$^{+26}_{−20}$. This calculation was based on matching the observed luminosity function and used membership probabilities calculated without any proper motion information. Now that we have an improved determination of the satellites’ LMC membership, we can update this calculation. This is done by taking the probabilities of being an LMC satellite from \cite{jethwa2016} and replacing them with 1 or 0 depending on how we have classified them in this work. If the satellites do not have 6d information (i.e. missing proper motions or radial velocities), we keep the probability as determined by Jethwa, Erkal & Belokurov (2016). We then compute the expected number of LMC satellites with these updated probabilities, compare this with the expectation value in \cite{jethwa2016}, and scale the total number of satellites by this ratio. This reduces the expected number of satellites slightly to 60. Thus we conclude that there is a large number of LMC satellites still to be found given that we have only identified 7 in this work.

5 CONCLUSIONS

This work confirms the LMC group infall found in \cite{kallivayalil2018} with an independent technique and extends the number of LMC satellites. In addition to the SMC, we identify six dwarf galaxies as being highly likely bound to the Cloud previously: Car 2, Car 3, Hor 1, Hya 1, Phe 2, and Ret 2. Furthermore, we find that there exist radial velocities for which Eri 3 has a significant probability of being an LMC satellite ($p_{\text{LMC}} > 0.4$). Having tested our method on cosmological simulations, we believe that dwarfs with a modest probability of being LMC satellites (i.e. Hor 2 and Tuc 4) should be reconsidered once additional (better) data is available. Tests with cosmological simulations also showed that as the observational errors are reduced, the certainty with which we can classify satellites as belonging to the LMC will improve.

Assuming that these 7 satellites identified here do belong to the LMC, we estimate that the Cloud’s mass should be $> 1.24 \times 10^{11} M_\odot$. This estimate is tested with a cosmological simulation where we find that given the current observational errors, this lower bound may be overestimated. As the observational errors are reduced, this lower bound will become more accurate and thus it should be revisited once better proper motions, e.g. from Gaia DR3, are available.

We also explore the orbits of the Milky Way satellites and find that several satellites have a large change in their orbit once the LMC is included. Most interestingly, in the presence of the LMC, the two satellites with small(er) pericentric passages with respect to the Milky Way. It is possible that tidal disruption on these adjusted orbits can naturally explain their diffuse properties (as proposed in Sanders, Evans & Dehnen 2018 and Torrealba et al. 2019) which shows that it is crucial to include the LMC when studying the evolution of Milky Way satellites.

The ability to distinguish LMC satellites from that of the Milky Way opens up the prospects of better understanding the ultra-faint dwarf satellites of both the Milky Way and the LMC. Previous analyses of the Milky Way satellites have avoided the dwarfs recently discovered in the DES data due to the possible contamination by the LMC (e.g. Jethwa, Erkal & Belokurov 2018). Since the ultra-faint dwarfs in DES are also some of the faintest satellites detected, the constraints these studies placed on the nature of dark matter can now be improved.

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This research made use of \texttt{IPython} (Perez & Granger 2007).
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python packages Numpy [van der Walt, Colbert & Varoquaux 2011], Matplotlib [Hunter 2007], and SciPy [Jones et al. 2001]. This research also made use of Astropy [a community-developed core Python package for Astronomy [Astropy Collaboration et al. 2013 [Price-Whelan et al. [2018].]

Satellite census and LMC mass
APPENDIX A: DWARF PROPERTIES

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Satellite census and LMC mass

Properties of dwarf satellites

| Dwarf | α *deg | δ *deg | Distance *kpc | v *km/s | μ *mas/yr | μ *mas/yr | Cμ *μas | Pos. | Dist. | RV | PM |
|-------|--------|--------|---------------|---------|-----------|-----------|---------|------|------|----|----|
| Likely LMC satellites |
| Car 2 | 114.1066 | −57.9991 | 36.2 ± 0.6 | 477.2 ± 1.2 | 1.886 ± 0.076 | 0.079 ± 0.070 | – | 1 | 1 | 2 | 3 |
| Car 3 | 114.6298 | −57.8997 | 27.8 ± 0.6 | 284.6 ± 3.4 | 3.035 ± 0.120 | 1.558 ± 0.136 | – | 1 | 1 | 2 | 3 |
| Hor 1 | 43.8700 | −54.1100 | 87.0 ± 12.0 | 112.8 ± 2.6 | 0.901 ± 0.070 | −0.583 ± 0.067 | – | 4 | 4 | 5 | 3 |
| Hya 1 | 37.3890 | −79.3089 | 27.6 ± 0.5 | 80.4 ± 0.6 | 3.865 ± 0.159 | −1.450 ± 0.135 | – | 6 | 6 | 6 | 3 |
| Phe 2 | 354.9975 | −54.4060 | 83.18 ± 7.66 | 32.9 ± 4.5 | 0.49 ± 0.11 | −1.03 ± 0.12 | −0.48 | 7 | 7 | 8 | 9 |
| Ret 2 | 53.9200 | −58.0500 | 32.0 ± 3.0 | 62.8 ± 0.5 | 2.393 ± 0.040 | −1.300 ± 0.048 | – | 4 | 4 | 10 | 3 |
| SMC | 13.1867 | −72.8286 | 62.1 ± 1.9 | 145.6 ± 0.6 | 0.772 ± 0.063 | −1.117 ± 0.061 | – | 11 | 12 | 13 | 14 |

Inconsistent with LMC origin

Table A1. Properties of dwarf satellite sample considered in this work. (1) Torrealba et al. (2018), (2) Li et al. (2018), (3) Simon (2018), (4) Rechol et al. (2015), (5) Koposov et al. (2015a), (6) Koposov et al. (2018), (7) Koposov et al. (2015a), (8) Fritz et al. (2019), (9) Pace & Li (2019), (10) Simon et al. (2015), (11) McConnachie (2012), (12) Graczyk et al. (2014), (13) Harris & Zaritsky (2006), (14) Kallivayalil et al. (2013), (15) Torrealba et al. (2019), (16) Fritz et al. (2019), (17) Kallivayalil et al. (2018), (18) Okamoto et al. (2006), (19) Dall’Ora et al. (2006), (20) Koposov et al. (2011), (21) Walsh et al. (2015), (22) Koch et al. (2009), (23) Munoz, Geha & Willman (2010), (24) Musella et al. (2009), (25) Simon & Geha (2007), (26) Torrealba et al. (2016a), (27) Fu, Simon & Alarcon Jara (2019), (28) Lavey et al. (2015a), (29) Longard et al. (2018), (30) Martin et al. (2016), (31) Fritz et al. (2018) (Note that we used the proper motions from the original arXiv version of this paper). (32) Walker et al. (2016), (33) Musella et al. (2012), (34) Martin et al. (2015), (35) Kirby, Simon & Cohen (2015), (36) Martin, de Jong & Rus (2008), (37) Belokurov et al. (2007), (38) Simon et al. (2011), (39) Belokurov et al. (2009), (40) Kirby et al. (2013), (41) Lavey et al. (2015a), (42) Kirby et al. (2017), (43) Deluca-Wagner et al. (2015b), (44) Simon et al. (2017), (45) Okamoto et al. (2006), (46) Garofalo et al. (2018), (47) Dall’Ora et al. (2012), (48) Willman et al. (2005), (49) Willman et al. (2011), (50) Gara Collaboration et al. (2015).