Dynamics of the Magellanic Clouds in a Lambda cold dark matter universe

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ABSTRACT

We examine Milky Way–Magellanic Cloud systems selected from the Millennium-II Simulation in order to place the orbits of the Magellanic Clouds in a cosmological context. Our analysis shows that satellites massive enough to be LMC analogues are typically accreted at late times. Moreover, those that are accreted at early times and survive to the present have orbital properties that are discrepant with those observed for the LMC. The high velocity of the LMC, coupled with the dearth of unbound orbits seen in the simulation, argues that the mass of the MW’s halo is unlikely to be less than $2 \times 10^{12} M_\odot$. This conclusion is further supported by statistics of haloes hosting satellites with masses, velocities and separations comparable to those of the LMC. We further show that: (1) LMC and SMC-mass objects are not particularly uncommon in MW-mass haloes; (2) the apparently high angular momentum of the LMC is not cosmologically unusual; and (3) it is rare for a MW halo to host a LMC–SMC binary system at $z = 0$, but high speed binary pairs accreted at late times are possible. Based on these results, we conclude that the LMC was accreted within the past four Gyr and is currently making its first pericentric passage about the MW.

Key words: Galaxy: formation – Galaxy: fundamental parameters – galaxies: formation – galaxies: kinematics and dynamics – Magellanic Clouds.

1 INTRODUCTION

The Milky Way (MW) and its satellite galaxies offer a unique laboratory for near-field cosmology. The proximity of MW satellites means that their stellar content is resolved and can be used as a probe of galaxy formation and evolution (Grebel 2005). Furthermore, with the high astrometric precision of instruments such as the Advanced Camera for Surveys on the Hubble Space Telescope (HST), it is now also possible to measure accurate proper motions for some of these satellites (e.g. Kallivayalil et al. 2006a; Kallivayalil, van der Marel & Alcock 2006b; Piatek et al. 2007; Piatek, Pryor & Olszewski 2008). These measurements have significantly improved constraints on the satellites’ orbital histories, and have also revealed some surprises. In particular, Kallivayalil et al. (2006a, hereafter K06) found that the velocity of the Large Magellanic Cloud (LMC) is approximately $380 \, \text{km} \, \text{s}^{-1}$, which is much larger than what typically had been assumed ($\lesssim 300 \, \text{km} \, \text{s}^{-1}$; e.g. Gardner & Noguchi 1996) in modelling the orbit of the LMC.

This large velocity has forced a reconsideration of the conventional picture of the orbital history of the MCs, wherein the MCs have made multiple passages about the MW over a Hubble time. K06 and Besla et al. (2007, hereafter, B07) analysed possible LMC orbits and divided them into two categories: early accretion, in which the LMC has made at least one complete orbit about the MW; and late accretion, where the LMC is currently making its first pericentric passage. Distinguishing between these two orbital histories has important consequences for our understanding of the Local Group’s assembly history and for the formation of the Magellanic Stream (Besla et al. 2010).

The high velocities of the Clouds also raise the question of whether the MCs’ orbits are typical of massive satellites in MW-like systems and whether they can provide information about the mass of the MW’s halo. B07 showed that the MCs are effectively on an unbound orbit if the MW’s mass is on the low end of current estimates ($\sim 10^{12} M_\odot$, consistent with the results of Xue et al. (2008) based on blue horizontal-branch stars). On the other hand, a massive MW halo ($\sim 2 \times 10^{12} M_\odot$) – in line with estimates based on the timing argument and satellite kinematics including data from Leo I (Li & White 2008; Watkins, Evans & An 2010) – implies that the LMC has a velocity that is substantially lower than the local escape speed.

Analyses of cosmological simulations indicate that unbound orbits are quite rare (van den Bosch et al. 1999; Vitvitska et al. 2002; Benson 2005; Khochfar & Burkert 2006; Diemand, Kuhlen & Madau 2007; Wetzel 2011); for example, Wetzel (2011) found
that less than 2 per cent of merging satellites have formally unbound orbits at all masses and redshifts. Sales et al. (2007) have shown that a non-negligible number of subhaloes in cosmological simulations can be scattered to high-energy orbits as the result of three-body encounters, but these subhaloes are dynamically required to be low-mass, likely rendering this mechanism irrelevant for the LMC. Almost all of these results are based on modelling dark matter haloes as point mass, Kepler potentials. This is a poor approximation to the true structure of dark matter haloes at small radii, however. The LMC, which is currently at \( \lesssim \) one-fifth the MW’s virial radius, is in precisely this regime. As a result, it is far from clear whether an unbound LMC would be highly unusual in a cosmological context.

The very existence of massive satellites such as the MCs can also be used to place constraints on the mass of the MW. If the LMC is typical for galaxies of its stellar mass, it likely had a dark matter mass of \([1–2] \times 10^{11} \, M_\odot\) before accretion by the MW (Boylan-Kolchin et al. 2010; Guo et al. 2010). The SMC has a stellar mass that is typical for haloes that are only a factor of 2–3 less massive than this. Boylan-Kolchin et al. (2010, hereafter BK10) used statistics of subhaloes from a large sample of simulated MW-mass haloes to conclude that MC-mass galaxies are rare if the MW has \( M \lesssim 10^{12} \, M_\odot\) but are much more typical if the MW has a massive dark matter halo (\( \sim 2.5 \times 10^{12}\)). These results were based purely on the masses of the MCs and MW, however, and did not include the additional constraints provided by the MCs’ orbits.

In this paper, we examine the orbits, accretion epochs and masses of MW–MC systems using the Millennium-II Simulation (MS-II; Boylan-Kolchin et al. 2009), which has sufficient mass resolution to probe SMC mass scales and a large enough volume to contain a large, statistical sample of MW-mass haloes. We use realistic – but still spherically symmetric – potentials that are expected for Lambda cold dark matter (CDM) dark matter haloes when computing orbital parameters in an attempt to accurately describe the orbits of MC analogues at small radii from their hosts.

Our goal is to investigate five main questions related to the MCs in order to place their orbital properties and masses in a cosmological context.

(i) How common are satellites with masses similar to those of the LMC and SMC within MW-mass haloes at redshift zero?

(ii) How typical is the LMC in terms of its orbital properties (e.g. energy and angular momentum)?

(iii) Are LMC-type satellites at \( z = 0 \) typically accreted early (having completed at least one pericentric passage about their hosts) or late (being on their first infall towards their hosts)?

(iv) How likely is it that the MCs were accreted as a binary system?

(v) What can we infer about host haloes from the properties of massive satellites such as the LMC?

Our work is structured as follows. Section 2 provides relevant details about the MS-II, describes our assumptions about the MW and MCs, and defines our subhalo samples. In Section 3.1, we determine the most likely accretion epoch for the LMC based on mass considerations. In Sections 3.2–3.4, we fold the orbital properties of the LMC into the analysis to distinguish between the early or late accretion scenarios. Section 4 explores the expected frequency of LMC/SMC-type companions about MW-type hosts based on the MCs’ expected infall masses. In Section 5, we examine potential LMC/SMC binary systems and their properties. Our results are discussed in Section 6; in particular, we assess the likelihood that the MCs are on their first passage about the MW (Section 6.2). We present our conclusions in Section 7.

2 METHODOLOGY

2.1 The MS-II

Our analysis of objects similar to the MC is based on the MS-II, a very large \( N \)-body simulation that follows the evolution of over ten billion particles in a periodic cube of \((137 \, \text{Mpc})^3\) from redshift 127 to 0. The cosmological parameters used in the MS-II are identical to those adopted for the MS (Springel et al. 2005) and the Aquarius simulations (Springel et al. 2008):

\[
\Omega_{\text{tot}} = 1.0, \quad \Omega_m = 0.25, \quad \Omega_b = 0.045, \quad \Omega_\Lambda = 0.75, \quad h = 0.73, \quad \sigma_8 = 0.9, \quad n_s = 1,
\]

where \( h \) is the Hubble constant at redshift zero in units of \( 100 \, \text{km s}^{-1} \, \text{Mpc}^{-1} \), \( \sigma_8 \) is the rms amplitude of linear mass fluctuations in \( 8 \, h^{-1} \, \text{Mpc} \) spheres at \( z = 0 \), and \( n_s \) is the spectral index of the primordial power spectrum. The MS-II offers a unique combination of mass resolution and large volume for studying dynamics of MC analogues within MW-mass systems: the MS-II particle mass of \( m_p = 9.43 \times 10^6 \, M_\odot \) results in over 100,000 particles in MW-mass haloes at \( z = 0 \), and resolves LMC-mass subhaloes with \( \gtrsim 10,000 \) particles. For further information about the MS-II, see Boylan-Kolchin et al. (2009).\(^1\)

2.2 MW-mass haloes

Current estimates of the mass of the MW’s halo range within \([1–3] \times 10^{12} \, M_\odot\) (e.g. Sakamoto, Chiba & Beers 2003; Battaglia et al. 2005; Dehnen, McLaughlin & Sachania 2006; Li & White 2008; Xue et al. 2008; Gnedin et al. 2010; Watkins et al. 2010; and references therein). In order to bracket this range, and to understand any trends with the mass of the MW, we select all haloes with \( 4.3 \times 10^{12} \leq M_{\text{vir}}/M_\odot \leq 4.3 \times 10^{13} \) from the MS-II at redshift zero as our primary ‘MW’ sample. This set is identical to that of Boylan-Kolchin et al. (2010) and contains approximately 7600 dark matter haloes, 2658 of which have \( M_{\text{vir}} \in [1–3] \times 10^{12} \, M_\odot\). It is important to note that not all of these haloes are expected to host MW-like galaxies in the standard CDM model: for example, approximately 30 per cent of haloes in our full MW sample should host galaxies that are not late-type based on their colours and specific star formation rates (Weinmann et al. 2006). By taking subsets of our main sample that are based on, e.g. environment, we can explore whether host halo properties correlate with the likelihood of hosting satellite galaxies like the MCs.

We use the radius inside of which the average density exceeds the critical density of the universe by a factor \( \Delta_{\text{crit}} \) (see Eke, Cole & Frenk 1996; Bryan & Norman 1998 for details) as the virial radius \( R_{\text{vir}} \) of our haloes, and the mass enclosed within this radius, \( M_{\text{vir}} \), as the virial mass. At redshift zero in the cosmology of the MS-II, \( \Delta_{\text{vir}} = 94.2 \) and the virial radius \( R_{\text{vir}} \) and virial (circular) velocity \( V_{\text{vir}} \) scale with the virial mass as

\[
R_{\text{vir}} = 257.8 \left( \frac{M_{\text{vir}}}{10^{12} \, M_\odot} \right)^{1/3} \, \text{kpc},
\]

\(^1\) Merger trees, along with halo and subhalo catalogues, from the MS-II are publicly available at http://www.mpa-garching.mpg.de/galform/millennium-II.
\[ V_{\text{vir}} = 129.2 \left( \frac{M_{\text{vir}}}{10^{12} M_\odot} \right)^{1/3} \text{ km s}^{-1}. \]  

We will use these relations in subsequent sections to scale measured properties of the MCs – e.g. their angular momenta – to the virial values for a range of virial masses for the MW.

Later sections will also focus on orbital properties of subhaloes within their hosts. These properties will be computed assuming that the host dark matter haloes are well fitted by Navarro, Frenk & White (1996, 1997, hereafter, NFW) density profiles. The structure of the NFW profile is fully specified by a halo’s mass and the radius at which the circular velocity curve peaks, \( R_{\text{max}} \). Using values of \( M_{\text{vir}} \) and \( R_{\text{max}} \) computed directly from the MS-II to set the NFW potential, we calculate the energy, angular momentum and eccentricity of orbiting subhaloes within MW-mass hosts. We defer an analysis of the current distance of the LMC from the MW to Section 6.3, as it is inherently extremely rare for a satellite to be near pericentre (as is the case for LMC) for the eccentric orbits typical of ΛCDM satellites (Tormen 1997; Diemand et al. 2007). Note that one limitation of our approach is the use of spherically symmetric profiles in our calculations, whereas haloes from cosmological dark matter simulations are typically prolate or triaxial (e.g. Warren et al. 1992; Jing & Suto 2002; Allgood et al. 2006; Bett et al. 2007).

2.3 The Magellanic Clouds

2.3.1 Observed properties

The LMC (SMC) is the most (second-most) luminous satellite of the MW. Following Kim et al. (1998), we assume that the stellar mass of the LMC is \( M_{\text{LMC}} = 2.5 \times 10^9 M_\odot \). We adopt a galactocentric distance of \( R_{\text{LMC}} = 50.1 \) kpc (Freedman et al. 2001). K06’s analysis of the LMC’s proper motion shows that

\[ V_{\text{LMC, tan}} = 367 \pm 18 \text{ km s}^{-1}, \]
\[ V_{\text{LMC, rad}} = 89 \pm 4 \text{ km s}^{-1}. \]

The specific angular momentum of the LMC, normalized by the specific angular momentum of a circular orbit at the MW’s virial radius, is therefore

\[ j_{\text{LMC}} = \frac{R_{\text{LMC}} V_{\text{LMC, tan}}}{V_{\text{vir}}} = 0.55 \left( \frac{M_{\text{vir}}}{10^{12} M_\odot} \right)^{-2/3}. \]  

We assume that the SMC is at a distance of 58.9 kpc (Kallivayalil et al. 2006b) and has a stellar mass of \( M_{\text{SMC}} = 3 \times 10^8 M_\odot \) (Stanimirović, Staveley-Smith & Jones 2004). The proper motion measurements of Kallivayalil et al. (2006b) give

\[ V_{\text{SMC, tan}} = 301 \pm 52 \text{ km s}^{-1}, \]
\[ V_{\text{SMC, rad}} = 23 \pm 7 \text{ km s}^{-1}. \]

From these values, the specific angular momentum of the SMC is

\[ j_{\text{SMC}} = \frac{R_{\text{SMC}} V_{\text{SMC, tan}}}{V_{\text{vir}}} = 0.53 \left( \frac{M_{\text{vir}}}{10^{12} M_\odot} \right)^{-2/3}. \]  

The angular momenta of the LMC and SMC are therefore strikingly close to each other.

We assume a fixed concentration of 10 when computing the potential of the actual MW. This is not a strong assumption, as changing the concentration between, e.g. eight and 12 does not significantly affect the inferred pericentre, angular momentum or orbital energy of the subhaloes.

Piatek et al. (2008) have performed an independent analysis of the HST proper motion data and find results that are in general agreement with, but at the lower end of, the range found by K06. In particular, Piatek et al. find \( (V_{\text{tan}}, V_{\text{rad}}) \) of \((346 \pm 8.5 \text{ km s}^{-1}, 93.2 \pm 3.7 \text{ km s}^{-1})\) and \((259 \pm 17 \text{ km s}^{-1}, 6.8 \pm 2.4 \text{ km s}^{-1})\) for the LMCs and SMCs, respectively. Adopting these values changes the normalization of equation (5) to 0.52 and of equation (7) to 0.46. Recently, Vieira et al. (2010) determined proper motions for the MCs using photographic and CCD observations from the Yale/San Juan Southern Proper Motion programme spanning a baseline of 40 yr. They also confirm the K06 results and find proper motions for the SMC that are more consistent with the Kallivayalil et al. (2006b) analysis than that of Piatek et al.

2.3.2 MCs in the MS-II

In order to identify \( z = 0 \) analogues of the LMC, we first search our full MW sample for all subhaloes that survive to \( z = 0 \) and reside within a fixed fraction of \( R_{\text{vir}} \) of their host (see below). For each of these subhaloes, we also find the mass of its main progenitor at all earlier times. To define analogues of the MCs in an N-body simulation such as the MS-II, we need a way to link dark matter (sub)haloes to galaxies. Recent work has shown that many observed statistical properties of galaxies can be reproduced under the simple ‘abundance matching’ assumption that stellar mass is a monotonically increasing function of the maximum dark matter mass a subhalo attains over its history (e.g. Conroy, Wechsler & Kravtsov 2006; Wang et al. 2006; Guo et al. 2010; Klypin, Trujillo-Gomez & Primack 2010; Moster et al. 2010). Accordingly, we select as our fiducial sample the subhalo with the largest maximum main progenitor mass in each halo; we will refer to this sample as the first-ranked subhaloes. The mass of this progenitor and the redshift at which it was reached are denoted \( M_{\text{acc}} \) and \( z_{\text{acc}} \); we will sometimes refer to these quantities as the infall mass and infall redshift. Note that subhaloes selected in this manner are not necessarily the most massive subhaloes in their hosts at \( z = 0 \).

We identify LMC analogues within this sample by adding two additional conditions. First, the host haloes must obey \( M_{\text{vir}} \in [1–3] \times 10^{11} M_\odot \), corresponding to approximately 35 per cent of our full host halo sample; note that this is in the upper end of our host sample in terms of mass. Next, we use abundance matching as implemented by Guo et al. (2010) to estimate the maximum dark matter halo mass of the LMC. With our definition of halo mass, the infall halo mass corresponding to the LMC’s stellar mass is \( M_{\text{LMC}}(z_{\text{acc}}) \approx 1.6 \times 10^{12} M_\odot \). We define LMC analogues as first-ranked subhaloes having infall masses within a factor of two of this mass, \( 8 < M_{\text{LMC}}(z_{\text{acc}}) \left[ 10^{10} M_\odot \right] < 32 \), which allows for both scatter in the \( M_{\text{vir}} - M_{\text{sub}} \) relation and uncertainty in the stellar mass of the LMC. Such subhaloes are more massive than the typical most massive subhalo, in terms of maximum progenitor mass, of MW-mass haloes (BK10; see Section 4 for a full analysis).

To identify SMC analogues, we first find the surviving subhaloes at \( z = 0 \) having the second-highest infall mass among all subhaloes of their hosts; we will refer to this fiducial sample as the second-ranked subhaloes. Using the SMC’s stellar mass, we select second-ranked subhaloes with masses between \( 4 \times 10^{10} \) and \( 1.6 \times 10^{11} M_\odot \) in hosts with \( M_{\text{vir}} \in [1–3] \times 10^{12} M_\odot \) as our SMC analogues. All SMC analogues therefore have at least 4000 particles at their maximum, well above the \( \sim 1500 \) particle requirement that Guo et al. (2010) show is necessary to adequately resolve the \( M_{\text{acc}} \) halo + subhalo mass function at \( z = 0 \) (see also Wetzel & White 2010).
It is important to choose a suitable limiting radius for defining each halo’s most (second-most) massive surviving subhalo. A natural choice is the redshift zero virial radius. We therefore consider the most (second-most) massive non-dominant subhalo within \( R_{\text{vir}} \) at \( z = 0 \) as our fiducial sample. The precise choice of limiting radius used is not particularly crucial, so long as the radius is sufficiently large to cover much of the halo; we find similar results for 0.65–1.0 \( R_{\text{vir}} \).

To summarize, we define two samples for both the LMC and the SMC.

(i) First-ranked subhaloes (1st):
the most massive subhalo, in terms of the maximum mass ever attained, located within \( R_{\text{vir}} \) of a host’s center at \( z = 0 \). This sample contains 7641 subhaloes.

(ii) LMC analogues:
the subset of 1st with \( 8 \times 10^{10} < M_{\text{acc}}/M_\odot < 3.2 \times 10^{11} \) located in hosts with virial mass \( M_{\text{vir}} \in [1–3] \times 10^{12} M_\odot \). This sample contains 938 subhaloes.

(iii) Second-ranked subhaloes (2nd):
the second most massive subhalo, in terms of the maximum mass ever attained, located within \( R_{\text{vir}} \) of a host’s centre at \( z = 0 \). This sample contains 7639 subhaloes.

(iv) SMC analogues:
the subset of 2nd with \( 4 \times 10^{10} < M_{\text{acc}}/M_\odot < 1.6 \times 10^{11} \) located in hosts with virial mass \( M_{\text{vir}} \in [1–3] \times 10^{12} M_\odot \). This sample contains 840 subhaloes.

3 ORBITAL PROPERTIES OF LMC CANDIDATES

3.1 First crossing time

The lookback time at which the LMC first crossed the physical \( z = 0 \) virial radius of the MW, moving inward – referred to hereafter as the first crossing time (\( t_{\text{fc}} \)) – serves as a useful discriminant between the early and late accretion scenarios laid out in B07. We therefore compute \( t_{\text{fc}} \) for all first-ranked haloes in our full MW sample to investigate whether there is a preferred accretion epoch for LMC-like objects.

The distributions of \( t_{\text{fc}} \) for all first-ranked subhaloes and for those in the LMC analogue subsample are shown in Fig. 1 as solid and dashed histograms, respectively. The full distribution is bimodal, with a primary peak at \( t \approx 8 \) Gyr and a secondary peak at \( t = 0 \) Gyr; the median value is \( t_{\text{fc}} = 5.8 \) Gyr. The distribution for the LMC-mass sample is markedly different. There is no prominent peak at \( t_{\text{fc}} \approx 8 \) Gyr; instead, the distribution rises continuously from large lookback times (high redshift) to the present day, and the median of the distribution lies at \( t_{\text{fc}} = 3.9 \) Gyr. The differences between the two distributions reflect the relatively high masses of the LMC analogue sample; since these subhaloes are more massive than the average first-ranked subhalo, they are accreted on to their host haloes later, in the typical hierarchical manner expected in the \( \Lambda \)CDM cosmology.

Candidates in the LMC’s expected mass range are usually accreted at fairly late times: only 12 per cent have \( t_{\text{fc}} > 7.5 \) Gyr (\( z_{\text{fc}} > 1 \)), while approximately 30 per cent have been accreted within the past 2 Gyr. Such numbers favour the late accretion scenario for the LMC. Even taking all first-ranked subhaloes (the solid line in the lower panel of Fig. 1), we find that \( \sim 70 \) per cent were accreted since \( z = 1 \). First-ranked subhaloes that could have completed several orbits are rare.

3.2 Angular momentum

Fig. 2 shows the cumulative distribution of specific angular momenta\(^3\) \( j = R V_{\text{tan}} \), normalized by the virial value \( j_{\text{vir}} = R_{\text{vir}} V_{\text{vir}} \). For

\(^3\)The angular momentum is computed with respect to the host’s centre, defined by the location of the gravitational potential minimum. The host’s velocity is determined by averaging over all particles in the host’s main subhalo. We have also tried computing the velocity with respect to only the most bound particles in the host subhalo or only those particles within 10 or 25 kpc and found that the results presented here are unchanged.
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331 km s\(^{-1}\) for the LMC on the LMC's tangential velocity. This allowed range is fairly small and includes errors on the tangential velocity, for a MW mass in the range \([1\text{--}3]\times10^{12}\,M_\odot\). Late-accreted LMCs typically have angular momentum lower than the observed range for the LMC. On the other hand, half of the LMC analogues accreted within the past 4 Gyr have angular momentum within the shaded region, supporting a late accretion scenario for the LMC.

Early accreted (>4 Gyr ago) LMC analogues in low-mass MWs are strongly disfavoured: even in the most extreme scenario of \(M_{\text{vir}} = 3\times10^{12}\) and \(V_{\text{tan,LMC}} = 331\,\text{km}\,\text{s}^{-1}\) (2\(\sigma\) lower than the central value of K06), we still find that over 50 per cent of LMC analogues have lower angular momentum than those accreted within the past 2 Gyr having angular momentum within the shaded region, supporting a late accretion scenario for the LMC.

Regardless of accretion epoch, approximately 30–35 per cent of LMC analogues fall in the grey shaded region; the LMC's angular momentum is not atypical in a cosmological context. This result dismisses previous assertions that tidal forces from M31 are needed to explain the orbital angular momentum of the LMC (e.g. Raychaudhury & Lynden-Bell 1989; Shuter 1992; Byrd et al. 1994). Originally, concerns about the LMC’s angular momentum arose because the orbital plane of the MCs is polar to the disc plane of the MW, while the LMC has orbital angular momentum that is at least as much as that of the MW’s thin disc (Fich & Tremaine 1991; Lin, Jones & Klemola 1995; Sawa & Fujimoto 2005). This is potentially difficult to explain in an early accretion scenario; torques from the MW’s disc certainly could not explain the angular momentum of the LMC in this configuration, leading to the search for alternate potential perturbers. While our analysis does not extend to the likelihood of a polar orbital orientation, we do find that the angular momentum of the LMC’s orbit is more typical in a recent accretion scenario. Over such short interaction time-scales, torques from the host are largely irrelevant and our result should hold regardless of the orientation of the orbit.

3.3 Energy

Fig. 3 shows the orbital energy distribution of the MS-II LMC analogues, normalized by the energy of a circular orbit at the host’s virial radius. A striking feature of Fig. 3 is that nearly all subhaloes are on bound orbits \((E \equiv E/E_{\text{circ}}(R_{\text{vir}}) > 0)\). The implications of the energies of subhalos’ orbits for the LMC are highly sensitive to the virial mass of the MW; less than 10 per cent of LMC analogues have orbits as energetic as that of the observed LMC if the MW’s virial mass is smaller than \(2 \times 10^{12}\,M_\odot\) (blue shaded region), while a substantial fraction have orbits that match the energy of the LMC’s orbit if the MW’s halo lies within the range \([2\text{--}3]\times10^{12}\,M_\odot\) (green shaded region). Even if we take both radial and tangential velocities that are 1\(\sigma\) (2\(\sigma\)) lower than mean values of K06, we still find that only 2.3 per cent (7.9 per cent) of orbits are more energetic than observed for the LMC in a halo of \(3.67\times10^{12}\,M_\odot\).

In Fig. 4 we show the cumulative distribution of \(E\) for the LMC analogue sample, split by accretion epoch (solid curves); the distribution for the full LMC analogue sample (Fig. 3) is shown as the green shaded region:

\[2 \times 10^{12} < M_{\text{MW}} < 3 \times 10^{12}\,M_\odot\]

Blue shaded region:

\[10^{12} < M_{\text{MW}} \lesssim 2 \times 10^{12}\,M_\odot\]

\[E \equiv E_{1/2}/E_{\text{circ}}(R_{\text{vir}}) - 1\]

...
dotted curve. There is a marked difference when looking at early (>4 Gyr) versus late (<4 Gyr) accreted LMCs. Early-accreted LMCs tend to be on much more bound orbits (higher values of $E$), while late-accreted LMCs are less bound to their host haloes (though virtually all are still bound, formally).

Using the mean velocities from K06, we find that a MW of mass $(1, 2, 3) \times 10^{12} \, M_\odot$ corresponds to $E = (-0.53, 1.21, 1.96)$. If the MW’s halo mass does not exceed $2 \times 10^{12} \, M_\odot$, the early accretion scenario is strongly disfavoured: there are vanishingly few early-accreted LMCs in the MS-II having $E < 1/2$. Fig. 4 also strongly disfavours any LMC accretion scenario for a $10^{12} \, M_\odot$ MW (which puts the LMC on an unbound orbit). Approximately 25 per cent of the late-accreted (and 7 per cent of the early-accreted) LMCs have binding energies lower than the observed LMC for a MW mass of $2 \times 10^{12} \, M_\odot$. The energetics favour a combination of a massive MW halo and a late-accreted LMC.

### 3.4 Eccentricity

To further explore the typical orbital properties of surviving LMC analogues as a function of accretion epoch, we consider the distribution of orbital eccentricities for these systems. Orbital eccentricity $e$ is here defined as a combination of the pericentres $r_p$ and apocenters $r_a$ of orbits:

$$e \equiv \frac{r_a - r_p}{r_a + r_p}$$

(We assign unbound orbits an eccentricity larger than 1.) With this definition, $e < 0.5$ corresponds to fairly circular orbits ($r_a/r_p < 3$), while $e = 0$ indicates a perfectly circular orbit.

Fig. 5 shows that early-accreted LMC analogues tend to be on orbits that are substantially more circular than those of late-accreted LMC analogues. Only 20 per cent of LMCs accreted within the last 2 or 4 Gyr (cyan and black solid lines, respectively) have $e < 0.5$, a value that is met by approximately 50 per cent of LMCs accreted over 4 Gyr ago and by 60 per cent accreted more than 8 Gyr in the past. Although late accretion does not account for a priori reason that the Clouds cannot have completed multiple pericentric passages, these data on eccentricities provide further constraints. The mean eccentricity for the late-accreted LMC analogues is $0.71$. Given that the pericentre of the LMC’s orbit is $\approx 45 \, \text{kpc}$, the resulting apocenter is $\approx 260 \, \text{kpc}$. The MCs clearly could not have completed multiple pericentric passages on such an orbit within the past 4 Gyr. We therefore conclude that the MCs were most likely accreted within the past 4 Gyr and are on their first passage about the MW.

Fig. 5 reinforces how unlikely it is to find an object with the LMC’s infall mass and orbit in a $10^{12} \, M_\odot$ halo at $z = 0$, regardless of accretion epoch, as the LMC has $e > 1$ according to our definition – i.e. the LMC’s orbit is unbound – for this mass. If the MW does have such a low-mass halo, then the LMC was certainly accreted within the past 4 Gyr. Moreover, less than 10 per cent of orbits – independent of accretion epoch – have $e > 0.92$, which corresponds to a halo mass of $< 1.5 \times 10^{12} \, M_\odot$. It is therefore quite unlikely that the MW has a mass of less than $1.5 \times 10^{12} \, M_\odot$. (For reference, a MW halo of mass $2 \times 10^{12} \, M_\odot$ results in an eccentricity of 0.79 for the LMC, while a mass of $3 \times 10^{12} \, M_\odot$ gives an eccentricity of 0.62.)

4 FREQUENCY OF LMC/SMC ANALOGUES ABOUT MW HOSTS

In this section, we examine the mass distribution of the samples defined in Section 2.3.2. Our goal is to determine how typical the infall masses of the MCs are relative to the full first- and second-ranked subhalo samples and as a function of the host mass. The upper left panel of Fig. 6 shows the distribution of masses for first-ranked subhaloes (solid histogram) and LMC analogues (dashed histogram), relative to the redshift zero virial mass of their...
hosts. The distribution of masses for first-ranked subhaloes is fairly broad and peaks at $M_{\text{vir}} \approx 0.03 M_{\odot}$ ($z = 0$). The mass distribution of LMC analogues is substantially narrower and peaks at a much higher mass, $M_{\text{LMC}} \approx 0.1 M_{\odot}$ ($z = 0$). The difference between the two distributions indicates that the LMC is more massive than the typical first-ranked satellite galaxy in a MW-mass halo, a conclusion also reached in BK10.

A similar situation exists for the SMC, which is shown in the upper right panel of Fig. 6. While the distribution of $\mu_{2\text{nd}}$ peaks at $\sim 0.01$, the distribution of $\mu_{\text{SMC}}$ peaks at $\sim 0.03$. This shows that the SMC is also more massive than the second-ranked galaxy in a typical MW-mass halo.

The solid line in the lower left panel of Fig. 6 shows the cumulative version of $M_{\text{1st}}(z_{\text{acc}})/M_{\text{vir}}(z = 0)$. The combined shaded region encompasses the full LMC analogue sample; the range of $M_{\text{acc}}/M_{\text{vir}}(z = 0)$ corresponding to $M_{\text{vir}} = 10^{12} M_{\odot}$ is shown in blue, while the range for $3 \times 10^{12} M_{\odot}$ is shown in grey. The lower right panel of Fig. 6 plots the same quantities for our sample of second-ranked subhaloes and SMC analogues.

Recall that there are 2658 host haloes in the mass range $M_{\text{vir}} \in [1-3] \times 10^{12} M_{\odot}$. If we define MC analogues strictly in terms of mass, we thus conclude that approximately 35 per cent of MW-mass haloes host an LMC analogue and 32 per cent host an SMC analogue within $R_{\text{vir}}$. These numbers are for a specific range of MW halo masses, however, and are sensitive to the precise mass of the MW (BK10). A halo of $10^{12} M_{\odot}$ has a $\approx 20$ per cent chance of hosting an LMC analogue, and less than a 10 per cent chance to host an SMC analogue. A $3 \times 10^{12} M_{\odot}$ MW makes LMC/SMC analogues much more common, as approximately 40 per cent of such hosts have LMC/SMC analogues. [Note that these numbers are likely to be upper estimates, as we have used very conservative estimates on the errors for the mapping between $M_1$ and $M_{\text{acc}}$.]

In a search for LMC analogues in the seventh data release of the Sloan Digital Sky Survey (York et al. 2000; Abazajian et al. 2009), Tollerud et al. (in preparation) determine that approximately 40 per cent of isolated hosts with luminosities similar to that of the MW also have an LMC analogue ($r$-band magnitude between $-17.5$ and $-20$) located within a projected separation of 250 kpc. Although the selection criteria of Tollerud et al. differ from those used here, this result appears consistent with our findings.

The mass of the first-ranked subhalo correlates strongly with its first crossing redshift $z_{\text{fc}}$, which is shown in Fig. 7. The median (middle curve) decreases from $z_{\text{fc}} \approx 1.4$ at $\mu = 0.01-0.4$ at $\mu = 0.1$ (70 per cent of the distribution is contained within the dashed curves). The shaded region in Fig. 7 shows the allowed range for the LMC when using the abundance matching assumption (see Fig. 6).

An alternate way of looking at the dependence of $\mu(1\text{st})$ on $z_{\text{fc}}$ is to divide the first-ranked subhaloes into two samples; those accreted early, defined here as $z_{\text{fc}} > 0.4$ (or equivalently, a look-back time of $t > 4$ Gyr, corresponding to the local minimum in Fig. 1), and those accreted at late times ($z_{\text{fc}} < 0.4$ or $t < 4$ Gyr). The result of this split is shown in Fig. 8 and reinforces the result of Fig. 7: first-ranked subhaloes that have joined their host within the last 4 Gyr tend to be a factor of $\sim 3$ more massive at infall than those

![Figure 6](https://academic.oup.com/mnras/article-abstract/414/2/1560/978248/1566-M.-Boylan-Kolchin-G.-Besla-and-L.-Hernquist?download=true)

Figure 6. The distribution of masses of first-ranked subhaloes (left-hand panels) and second-ranked subhaloes (right-hand panels) with respect to the virial mass of their hosts. Upper panels: distribution of $M_{\text{1st}}/M_{\text{vir}}(z = 0)$ and $M_{\text{LMC}}/M_{\text{vir}}(z = 0)$ (solid and dashed histograms, left-hand panel), and of $M_{\text{2nd}}/M_{\text{vir}}(z = 0)$ and $M_{\text{SMC}}/M_{\text{vir}}(z = 0)$ (solid and dashed histograms, right-hand panel). Lower panels: cumulative distributions of solid curves from upper panels. The shaded regions correspond to the observed range of infall masses for the LMC (left-hand panel) and SMC (right-hand panel) assuming a MW mass of either $10^{12} M_{\odot}$ (blue region) or $3 \times 10^{12} M_{\odot}$ (grey region).
that joined their host halo more than 4 Gyr ago. Since the LMC has been shown to be more massive than the typical-ranked halo (see Section 4), it is more likely to have been accreted at late times.

In order to assess whether a late or early accretion scenario is more plausible for the LMC, we need to also account for the survivability/mass-loss expected for LMC analogues, which will depend on the accretion epoch and the specific orbit of the subhalo. Fig. 9 shows the distribution of accretion mass relative to redshift zero dark matter mass$^4$ for LMC analogues. Results are plotted for early (more than 4 Gyr ago; cyan) and late (less than 4 Gyr ago; black) accretion epochs, as well as for very early (more than 8 Gyr ago; grey) and very recent (less than 2 Gyr ago; cyan) accretion epochs. There is a pronounced, and not unexpected, trend for stronger mass-loss in earlier accreted LMC analogues. The most recently accreted LMCs tend to be 3.5 to 30 times less massive. It is unlikely that the LMC could have undergone strong tidal stripping without losing much of its gas, which is at odds with observations.

Massive satellites typically do not survive for long before merging with their hosts: the dynamical friction time-scale for a 1:10 object at $z = 1$ is approximately 5 Gyr (Boylan-Kolchin, Ma & Quataert 2008), shorter than the time between $z = 1$ and the present day. This is corroborated by Stewart et al. (2008), who showed that LMC-mass objects ($M \sim 10^{11} M_\odot h^{-1}$) typically do not survive for more than $\sim 3$ Gyr after accretion (their fig. 5). BK10 examined the accretion epochs of massive subhaloes in MW-mass hosts and found the same trend (their fig. 12). Both groups argued, as we do here, that this lends support to a first passage scenario for the LMC.

$^4$ This is the bound mass determined by the SUBFIND algorithm.
These observations lead to a number of questions regarding the MC system, including: What is the probability that the MCs were accreted together and survive as a binary today? Is there a preferred accretion epoch or mass ratio for such a pair? How likely is it that the Clouds are only an apparent binary system today rather than a true binary system?

To this end, we consider the difference in accretion epoch between each MC analogue and the corresponding second-ranked halo about the same host. Fig. 10 shows the median difference (solid line) in $t_{fc}$ for the MC analogues and second-ranked subhaloes as a function of $t_{fc}$ for the LMC analogue, as well as the 10 per cent (dotted) and 25 per cent (dashed) quantiles. It is indeed possible to find first and second-ranked subhaloes that are accreted as pairs (within 1 Gyr of each other). This probability depends on the LMC accretion epoch, however, and does not provide information about whether the accreted pairs can remain as a binary to the present day. The number of pairs accreted $>4$ Gyr is approximately three times larger than the number accreted within the last 4 Gyr. This is likely a result of 1 Gyr being a much larger fraction of a typical orbital time at higher redshifts than today.

We can also compute how likely it is to find MC-like objects around MW-mass hosts in a binary system at $z = 0$. To do so, we calculate the separation in position and velocity space between the LMC analogue sample and the corresponding second-ranked subhalo for the same host. Systems having $|\Delta v| < 150 \text{ km s}^{-1}$ and $|\Delta R| < 50 \text{ kpc} \text{ h}^{-1}$ are considered plausible binaries. Table 1 lists a number of properties for the 23 identified LMC/SMC analogues, including the first crossing time for each Cloud. Recall that the LMC analogue sample contains 938 haloes; it is thus possible, though not probable ($\sim 2.5$ per cent), that an LMC analogue and a second ranked halo be found in a binary system about a MW-mass host today.

Since SMC analogues represent a subset of the second ranked subhalo sample, these numbers also indicate that LMC / SMC analogues accreted at similar epochs are not likely to exist as binaries at the present day. The binaries that do survive to $z = 0$ tend to have the SMC in an eccentric orbit about the LMC. This in agreement with the proper motion measurements of the SMC by Kallivayalil et al. (2006b) and Vieira et al. (2010), who find a high relative velocity between the Clouds. An eccentric SMC orbit about the LMC is also required in the Magellanic-Stream model proposed by Besla et al. (2010). The present study shows that such an orbital configuration is cosmolgically expected.

A few specific cases from Table 1 stand out in particular. The first three rows have the pairs that were accreted most recently. All three of these systems have more angular momentum than the true LMC, highlighting that there may be no issue with the large magnitude of the LMC angular momentum if it was accreted recently. Additionally, all are on fairly energetic orbits: with $E/E_{\text{vir}} \approx 1$, they are the most energetic among all 23 binary candidates. In fact, most of the other candidates have $E/E_{\text{vir}} \gtrsim 2$, which places them on orbits that are improbably bound (relative to the observed LMC) even for a MW of $10^{12} M_{\odot}$ (see Fig. 3). With the exception of the oldest binary candidate (the final row of Table 1), all systems with $t_{fc}(\text{LMC}) > 5$ Gyr have low angular momentum, likely due to losses via dynamical friction. Although the volume of the MS-II does not provide a vast sample of possible binaries, those that do exist with orbital energetics similar to that observed for the Clouds are accreted at late times. Specifically, the systems highlighted in the first three rows of Table 1 illustrate that it is possible for a binary LMC/SMC to be accreted very recently on a high angular momentum/orbital energy orbit.

A further point of interest is that the pairs with first crossing redshifts that differ by $\gtrsim 2.5$ Gyr between the LMC and the

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**Table 1.** Properties of LMC–SMC binaries. Column 1: ratio of masses of most massive progenitors; column 2: mass ratio at $z = 0$; column 3: first crossing time for LMC; column 4: first crossing time for SMC; column 5: separation between LMC and centre of host; column 6: 3D velocity of the LMC, relative to host.

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<th>$M_{L}/M_{S}$ ($z = 0$)</th>
<th>$M_{L}/M_{S}$ ($z = 0$)</th>
<th>$t_{fc, LMC}$ (Gyr)</th>
<th>$t_{fc, SMC}$ (Gyr)</th>
<th>$R_{LMC}$ (kpc)</th>
<th>$V_{LMC}$ (km s$^{-1}$)</th>
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<td>8.58</td>
<td>7.91</td>
<td>107.39</td>
<td>229.95</td>
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</table>

*Note that the calculation of subhalo masses at redshift zero is sensitive to the location of the subhaloes within their hosts.*
corresponding second ranked subhalo are all cases where the LMC is within 100 kpc of the host. If these systems were true binaries, then there should also exist examples where the two subhaloes had discrepant accretion epochs and are located at large distances from the host today. Since no such examples exist, it is likely that these are chance associations of two satellites near pericentre than true binaries.

6 DISCUSSION

Using the MS-II, we have investigated ΛCDM predictions for orbital properties and accretion histories of the MCs in the context of the updated proper motion measurements of Kallivayalil et al. (2006a,b). In this section, we further explore how environmental or cosmological parameters may influence our results, the likelihood that the MCs are on their first passage about the MW, and the masses of haloes hosting subhaloes with LMC-like separations and velocities.

6.1 MW sample

It is important to investigate whether the trends shown in the previous sections have any systematic dependence on any properties of the host haloes. In particular, haloes residing in low-density environments have different accretion histories than those in high-density regions (Gottlöber, Klypin & Kravtsov 2001; Maulbetsch et al. 2007; Fakhouri & Ma 2010), an effect that could potentially bias our results on accretion epochs of LMC analogues. We therefore plot how the large-scale environment of a halo influences the first crossing redshift of LMC analogues in Fig. 11. This plot shows that zfc is essentially independent of environment as measured by the dark matter overdensity, smoothed with a Gaussian filter of width 5 h⁻¹ Mpc. Our results should therefore be insensitive to the environment of the host halo.

![Figure 11. Dependence of zfc on the large-scale overdensity, measured via Gaussian smoothing on 5 h⁻¹ Mpc spheres, for the LMC analogues. There is no obvious dependence of zfc on the large-scale overdensity, indicating that the large-scale environments of MW-mass hosts does not strongly influence the accretion epochs of their most massive subhaloes.](https://academic.oup.com/mnras/article-abstract/414/2/1560/978248)

The typical accretion epoch of LMCs could also be affected by the choice of cosmology in the MS-II, which has σ₈ that is approximately 10 per cent higher than the current best-fitting value of ≈0.81 (Komatsu et al. 2009). (This difference is minor in terms of the number of MW-mass haloes found at z = 0, as it affects the abundances of such haloes by 10 per cent.) While a quantitative understanding of the effects of varying σ₈ would require running a completely new simulation, we can easily estimate the qualitative effect by noting that lowering σ₈ results in later formation of haloes of a given mass. We therefore expect that any changes due to reducing σ₈ would tend towards even later accretion epochs for LMC (and SMC) analogues.

Alternatively, we can note that σ₈(z = 0.21) ≈ 0.81 for the MS-II cosmology; the difference between the distribution of t₀c for haloes defined at this epoch and at z = 0 should therefore inform us about potential differences due to changes in the power spectrum normalization. The distribution of first crossing times for first-ranked subhaloes and LMC analogues of haloes selected from the MS-II at z = 0.21 (using the same criteria described in Section 2) is shown in Fig. 12. Comparing this distribution with the distribution of t₀c in haloes selected at z = 0 (the upper-hand panel of Fig. 1), we can see that little changes between z = 0 and 0.21. Accordingly, reducing σ₈ from the Millennium and MS-II value of 0.9 is not likely to strongly affect our findings on the accretion epochs of LMC-like satellites.

6.2 Are the MCs on their first passage about the MW?

A number of lines of observational evidence support the idea that the MCs are making their first pericentric pass about the MW. This scenario explains why two gas-rich satellites reside at small galactocentric distances – similar satellites are typically found at much larger distances from the MW or M31 (van den Bergh 2006) – as the Clouds would not have had sufficient interaction with the MW to have lost their gas by some combination of tidal stripping,

![Figure 12. Distribution of first crossing times for the sample of MW-mass hosts selected at z = 0.21 (analogous to upper panel of Fig. 1). This distribution is similar to the distribution for z = 0 hosts, suggesting that changing σ₈ from 0.9 to 0.815 should not affect our conclusions on the probability of the LMC being on its first pass about the MW.](https://academic.oup.com/mnras/article-abstract/414/2/1560/978248)
harassment, and ram pressure stripping (Mayer et al. 2006). Similarly, the unusually blue colour of the LMC (James & Ivory 2011; Tolliver et al., in preparation) means that it must have retained a substantial amount of star-forming gas, which is difficult to understand if the MCs have completed multiple orbits about the MW. The existence of stellar populations extending as far as $\approx 20$ kpc from the LMC’s dynamical centre (Muñoz et al. 2006; Majewski et al. 2009; Saha et al. 2010) is also an indication that the LMC has not interacted strongly with the MW. Finally, Besla et al. (2010) have shown that the Magellanic Stream may originate from a tidal interaction between the MCs themselves, a model that requires the MCs to be a recently accreted binary system.

B07 first examined the possibility that the MCs have been recently accreted by the MW using an orbital analysis constrained by the new HST proper motion measurements. Uncertainties in modelling the MW meant that a scenario in which the Clouds were accreted at early times cannot be ruled out by such an analysis (e.g. Gardiner & Noguchi 1996; B07; Shattow & Loeb 2009), and refinements in the error space of the proper motions are unlikely to improve this situation. (We note, however, that early accretion models assume a static MW halo potential over a Hubble time, which is unrealistic.) We have computed the likelihood of a first passage scenario using a large sample of MW-mass haloes from a high-resolution cosmological simulation of the CDM cosmology. Our results put the first passage scenario on even firmer ground. We have showed that it is highly improbable for surviving satellites with infall masses similar to that of the LMC to have been accreted at $z > 1$, rendering an early infall scenario unlikely based on mass considerations alone. We further found that 25 per cent of surviving LMC analogues have been accreted within the past $2 \, \text{Gyr}$ and that the energetics of the LMC orbit are strongly inconsistent with the properties of LMC analogues accreted $>4 \, \text{Gyr}$ ago. Finally, we have showed that recently accreted LMCs are incapable of making multiple pericentric passages by the present. Taken together, these results demonstrate that it is quite likely that the MCs have recently joined the MW and are currently making their first pericentric pass; a very recent accretion ($\lesssim 2 \, \text{Gyr}$ ago) is also cosmologically plausible.

6.3 Mass of the MW
Uncertainties in the mass of the MW’s halo play a substantial role in placing the LMC and its orbit in a cosmological context, as has been shown repeatedly in our analysis. A low-mass halo ($M_{\text{vir}} \approx 10^{12} M_{\odot}$) means that the LMC is fairly unusual in terms of (its high) mass and that it is very unusual in terms of its (energetic) orbit. Both the mass and orbital energy of the LMC are more typical for haloes of $M_{\text{vir}} \gtrsim 2 \times 10^{12} M_{\odot}$.

We can also take an ‘inverse’ view and ask, in what mass dark matter halo do objects with masses, velocities and halo-centric distances similar to the LMC reside? To this end, we build a sample of LMC analogues with no constraint on the properties of the host halo (note that this differs from the mass-selected samples used up to this point). We merely require the following properties of the subhalo: (1) $0.8 < M_{\text{acc}}/10^{11} M_{\odot} < 3.2$, (2) $35 < R < 65 \, \text{kpc}$ from its host, and (3) $300 < V_{\text{vir}} < 420 \, \text{km\,s}^{-1}$. Since these criteria are somewhat restrictive, we search for hosts in all 10 MS-II snapshots with $z < 0.3$. We find 495 subhaloes matching our search criteria; the distribution of host halo masses for these matches are shown in Fig. 13. The figure confirms that satellites with properties similar to those of the LMC are unlikely to reside in host haloes with $M_{\text{vir}} \lesssim 1.5 \times 10^{12} M_{\odot}$. If we further require that $M_{\text{vir}} < 3 \times 10^{12} M_{\odot}$, we still find that approximately 70 per cent of hosts of LMC-like subhaloes reside in hosts with $M_{\text{vir}} > 2 \times 10^{12} M_{\odot}$.

7 CONCLUSIONS
The new HST proper motions for the MCs (Kallivayalil et al. 2006a,b) have forced us to re-evaluate our understanding of their orbital history about the MW. The canonical picture, wherein the MCs are on a quasi-periodic, slowly decaying orbit around the MW, has been thrown out. We are left instead with two possibilities: (1) the MCs are on their first passage about the MW (late accretion); or (2) the MCs joined the MW $> 8 \, \text{Gyr}$ ago and are now on a highly eccentric orbit, having already completed at least one passage about the MW since infall (early accretion).

In this work, we have addressed the likelihood of these two scenarios by using the MS-II to place the MCs in a cosmological context in terms of their accretion epoch, orbital properties and masses. Our primary results can be summarized as follows. (i) LMC analogues are accreted preferentially at late times. Only 15 per cent have $t_{\text{inf}} > 7.5 \, \text{Gyr}$ ($z_{\text{inf}} > 1$), while approximately 30 per cent have been accreted within the past $2 \, \text{Gyr}$. Such numbers favour the late accretion scenario for the LMC.

(ii) The LMC’s angular momentum is not anomalously high. $30–35$ per cent of all LMC analogues have specific angular momentum matching that of the real LMC if the mass of the MW lies within $[1–3] \times 10^{12} M_{\odot}$. The angular momentum of the LMC is more typical of haloes at the massive end of this range than of those at the low-mass end.

(iii) It is exceedingly unlikely for the LMC to be on an unbound orbit. If the mass of the MW is less than $2 \times 10^{12} M_{\odot}$, the LMC has an orbit that is more energetic than 90 per cent of comparable systems (adopting the mean radial and tangential velocities of K06). 40 per cent of MW systems with $M_{\text{vir}} \in [2–3] \times 10^{12} M_{\odot}$ have an LMC analogue with orbital energy comparable to that of the LMC. It is highly unlikely for LMC-like subhaloes to be on unbound orbits,
which is the case for a low-mass MW, and none of the early-accreted LMCs are on unbound orbits. The conclusion that the LMC is in fact bound to a massive MW, and yet accreted recently, cautions against the use of backward orbital integration schemes to determine the orbital histories of satellites over cosmic time.

(iv) Energetically, it is difficult to accommodate a scenario where the MCs have made multiple pericentric passages. LMCs accreted at early times are on mostly circular orbits, at odds with observations. LMCs accreted recently have not had time to complete more than one pericentric passage.

(v) LMC and SMC-mass objects are not particularly uncommon in MW-mass haloes. In a refinement of the results presented in Boylan-Kolchin et al. (2010), we find that 20–32 per cent of MW-mass haloes host an LMC analogue and 10–25 per cent host an SMC analogue. These results are consistent with the analysis of LMC analogues about MW type hosts located in the SDSS DR7 by Tollerud et al. (in preparation). The MCs become less typical if the host halo is lower in mass.

(vi) It is possible, but not probable, to find LMC–SMC binaries at \( z = 0 \). We find a small number of MW-mass systems (\( \lesssim 2.5 \) per cent) with LMC analogues have apparent LMC–SMC binaries.

(vii) Subhaloes with properties similar to that of the LMC reside preferentially in massive host haloes. Out of all dark matter haloes (without restriction on mass) hosting objects with masses, velocities and separations similar to the LMC, only 10 per cent have \( M_{\text{vir}} > 2 \times 10^{12} M_{\odot} \), and less than 5 per cent have \( M_{\text{vir}} < 1.5 \times 10^{12} M_{\odot} \).

Overall, our results support a scenario in which the LMC is a recent addition (in the last 4 Gyr) to a fairly massive (\( M_{\text{vir}} \gtrsim 1.5 \times 10^{12} M_{\odot} \)) MW.

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