Clues to the ‘Magellanic Galaxy’ from cosmological simulations

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ABSTRACT
We use cosmological simulations from the Aquarius Project to study the orbital history of the Large Magellanic Cloud (LMC) and its potential association with other satellites of the Milky Way (MW). We search for dynamical analogues to the LMC and find a subhalo that matches the LMC position and velocity at either of its two most recent pericentric passages. This suggests that the LMC is not necessarily on its first approach to the MW, provided that the virial mass of the MW is as high as that of the parent Aquarius halo; \( M_{200} = 1.8 \times 10^{12} \) \( M_\odot \). The simulation results yield specific predictions for the position and velocity of systems associated with the LMC prior to infall. If on the first approach, most should lie close to the LMC because the Galactic tidal field has not yet had enough time to disperse them. If on the second approach, the list of potential associates increases substantially because of the greater sky footprint and velocity range of LMC-associated debris. Interestingly, our analysis rules out an LMC association for Draco and Ursa Minor, two of the dwarf spheroidals suggested by Lynden-Bell & Lynden-Bell to form part of the ‘Magellanic Ghostly Stream’. Our results also indicate that the direction of the orbital angular momentum is a powerful test of LMC association. This test, however, requires precise proper motions, which are unavailable for most MW satellites. Of the four satellites with published proper motions, only the Small Magellanic Cloud is clearly associated with the LMC. Taken at the face value, the proper motions of Carina, Fornax and Sculptor rule them out as potential associates, but this conclusion should be revisited when better data become available. The dearth of satellites clearly associated with the Clouds might be solved by wide-field imaging surveys that target its surroundings, a region that may prove a fertile hunting ground for faint, previously unnoticed MW satellites.

Key words: galaxies: evolution – galaxies: formation – galaxies: haloes – galaxies: kinematics and dynamics – Magellanic Clouds.

1 INTRODUCTION
The Large and Small Magellanic Clouds (LMC and SMC, respectively) are unusual satellite galaxies. They are exceptionally bright and so close to the Milky Way (MW) that recent studies have concluded that fewer than one in 10 MW-like systems are expected to host satellites with properties similar to the Clouds (Busha et al. 2010a; Boylan-Kolchin, Besla & Hernquist 2011; Guo et al. 2011; Lares, Lambas & Domínguez 2011; Liu et al. 2011; Tollerud et al. 2011). The short crossing time at their present Galactocentric distance suggests that they may have already completed a number of orbits in the Galactic potential (Murai & Fujimoto 1980; Lin & Lynden-Bell 1982; Gardiner, Sawa & Fujimoto 1994; van der Marel et al. 2002) while their proximity suggests that they form a bound pair.

If the LMC/SMC are truly physically associated, then it is likely that they were once part of a larger system: the ‘Greater Magellanic Galaxy’, to quote Lynden-Bell (1982). This idea has prompted searches for evidence that other satellites might have been in the past associated with the Clouds. This is encouraged, in part, by the ‘polar’ distribution of the brightest Galactic satellites, which seems to trace the orbital path of the Clouds (Lynden-Bell 1976). Lynden-Bell & Lynden-Bell (1995), for example, suggested a possible association between the LMC, SMC, Draco (Dra), Ursa Minor, Carina (Car) and Sculptor (Scl) as part of a common ‘Ghostly Stream’.

The association between different satellites has recently received renewed attention, motivated mainly by coherence in the
position and velocities of satellite pairs such as Leo IV and Leo V (Belokurov et al. 2008) and of satellites near the Sagittarius stream, e.g., Segue 1 (Niederste-Ostholt et al. 2009), Bootes II (Koch et al. 2009) and Segue 2 (Belokurov et al. 2009). These ideas have received support from the realization that most satellites should have been accreted into the MW as part of multiple systems and have gained momentum because testing the predictions of such scenario has become possible using realistic cosmological simulations (Sales et al. 2007b; D’Onghia & Lake 2008; Li & Helmi 2008; Ludlow et al. 2009; Klimenkov et al. 2010).

The Magellanic Clouds are also unusual in their kinematics. The latest proper motion measurements of stars in the LMC (Kallivayalil et al. 2006; Piatek, Pryor & Olszewski 2008) indicate that the LMC has a much higher tangential velocity than previously thought ($V_t \sim 370$ km s$^{-1}$), raising questions as to whether the LMC and SMC are actually bound to each other or even to the Galaxy as a whole. Besla et al. (2007), for example, have used the new kinematic data to revise earlier orbital models (see, e.g., van der Marel et al. 2002) and concluded that the LMC and SMC must be on the first pericentric passage of their orbit around the MW if the MW virial mass is of the order of $\sim 10^{12} M_\odot$, as argued by Klypin, Zhao & Somerville (2002).

The discussion above depends sensitively on the assumed virial mass of the Galaxy. Bright satellites are more common around more massive primaries (Guo et al. 2011), and higher primary masses make it easier to accommodate high orbital speeds for the satellites. Even a factor of 2 increase in virial mass can make a difference (Piatek et al. 2008; Shattow & Loeb 2009), which is certainly within the current uncertainty in virial mass estimates for the MW (Battaglia et al. 2005; Sales et al. 2007a; Smith & et al. 2007; Li & White 2008; Xue et al. 2008; Reid et al. 2009; Gnedin et al. 2010).

The escape speed at $r = 50$ kpc from a Navarro–Frenk–White (NFW) halo with the virial mass $M_{200} = 2 \times 10^{12} M_\odot$ is of the order of $\sim 500$ km s$^{-1}$, which would mean that the Clouds are safely bound to the Galaxy despite their high speed. Furthermore, Besla et al. (2007) show that virial masses as high as that imply a radial period of just about 3 Gyr and hence the possibility that the LMC and SMC have completed multiple orbits around the Galaxy. A first infall scenario is, on the other hand, compelling for a number of reasons, including the recent successful modelling of the Magellanic Stream as a tidal relic of a recent interaction between the Clouds before infall into the MW (Besla et al. 2010).

The discussion above highlights the fact that basic issues such as whether the LMC and SMC are on their first approach, or bound to each other, or truly associated with other MW satellites, remain unresolved. These questions are clearly interrelated. For example, the relative positions and velocities of satellites of past LMC associates would be very different if the Clouds are on the first or second approach. Careful modelling is therefore required to interpret the current data, especially because the orbit of the Clouds should be eroded quickly by the dynamical friction and by tidal mass-loss, limiting the applicability of models such as that of Besla et al. (2007), which assume that the Clouds evolve in a rigid Galactic potential.

We address these issues here by using the Aquarius Project, a series of cosmological simulations of the formation of a MW-sized halo in the Λ cold dark matter (ΛCDM) paradigm (Springel et al. 2008). Because of their extraordinary numerical resolution, we are able to trace the orbits not only of massive subhaloes, but also of subhaloes within subhaloes, thus enabling a realistic assessment of their orbital paths before, during and after their accretion into the MW halo.

This paper is organized as follows. In Section 2 we provide a brief description of the Aquarius simulations. We analyse the orbit of an LMC candidate in Section 3.1, and the spatial and kinematic properties of their associated subhaloes in Section 3.2. We use these results to explore in Section 3.3, which satellites of the MW might have been associated with the Clouds in the past. Section 4 summarizes our main conclusions.

## 2 THE NUMERICAL SIMULATIONS

### 2.1 The Aquarius Project

The Aquarius Project (Springel et al. 2008) is a series of cosmological simulations of the formation of six dark matter haloes with the mass consistent with that expected for the halo of the MW. The simulations assume the ΛCDM cosmology, with parameters chosen to match the Wilkinson Microwave Anisotropy Probe 1-year data (Spergel et al. 2003): the matter density parameter, $\Omega_M = 0.25$; cosmological constant term, $\Omega_\Lambda = 0.75$; power spectrum normalisation, $\sigma_8 = 0.9$; spectral slope, $n_s = 1$; and Hubble parameter, $h = 0.73$.

The haloes were identified in a large $N$-body simulation of a cube $137 (100 h^{-1})$ Mpc comoving on a side, a lower resolution version of the Millennium-II Simulation (Boylan-Kolchin et al. 2009). This volume was resimulated using the same power spectrum and phases of the original simulation, but with additional high-frequency waves added to regions encompassing the initial Lagrangian volume of each halo. The high-resolution region was populated with low-mass particles and the rest of the volume with particles of higher mass (Power et al. 2003).

The six Aquarius haloes are labelled ‘Aq-A’ through ‘Aq-F’. Each was resimulated at different resolutions in order to assess numerical convergence. A suffix, 1–5, identifies the resolution level, with level 1 denoting the highest resolution. Between levels 1 and 5, the particle mass ranges from $m_p = 2 \times 10^6 M_\odot$ to $3 \times 10^3 M_\odot$. At $z = 0$, the six haloes have similar ‘virial’ mass, roughly between $1 \times 10^{12} M_\odot$. For further details of the Aquarius Project, we refer the reader to Springel et al. (2008) and Navarro et al. (2010).

### 2.2 Identification of the LMC analogue

We search the Aquarius simulations for accretion events that result in systems with kinematics similar to that of the LMC. In particular, we look for relatively massive systems (i.e. with masses exceeding 1 per cent of the main halo mass) that are accreted relatively recently (i.e. after $z = 1$), and that have, at pericentre, distances and velocities of the order of 50 kpc and 400 km s$^{-1}$, respectively.

Our best candidate is a system that accretes into the main Aq-A halo at $z = 0.51$ ($t = 8.6$ Gyr, i.e. $\sim$5 Gyr before the present time). Just before accretion, at $t_A = 0.9$ ($t_A = 6.6$ Gyr), this subhalo has a virial mass of $M_{200} = 3.6 \times 10^{10} M_\odot$. Our analysis below focuses on this ‘LMC analogue (LMCa)’ halo and its substructures associated with the same friends-of-friends group (‘LMCa group’, for short) in the Aq-A-3 simulation. This level 3 simulation has a particle mass $m_p = 4.9 \times 10^4 M_\odot$, and therefore LMCa is resolved with more than 700 000 particles.

SUBFIND (Springel, Yoshida & White 2001) is used to identify self-bound substructures within LMCa; at $t_A$ there...
are more than 250 LMCa subhaloes with masses exceeding $1 \times 10^6 \, \text{M}_\odot$.

As may be seen from Fig. 1, the LMCa group turns around at $t_a = 5 \, \text{Gyr}$ ($z = 1.3$) from a distance of $r_a = 480 \, \text{kpc}$ (all distances and velocities quoted are physical unless explicitly stated otherwise). LMCa reaches its first pericentre at $t_{1p} = 9.5 \, \text{Gyr}$, with the pericentric distance ($r_{1p} = 63 \, \text{kpc}$) and speed ($V_{1p} = 355 \, \text{km s}^{-1}$) comparable to those of the LMC. The LMCa orbit becomes substantially more bound after the first pericentre due to dynamical friction and tidal mass-loss, so that it reaches a distance of only $240 \, \text{kpc}$ at its second apocentre, at $t = 11.5 \, \text{Gyr}$. Its radial period reduced to $3.8 \, \text{Gyr}$; it goes through pericentre again at $t_{2p} = 13.3 \, \text{Gyr}$, with the similar pericentric distance and speed as the first (see the right-hand panel of Fig. 1).

The best match to the kinematic properties of the LMC occurs just after each of these pericentric passages, at times that we will denote $t_{1p}$ and $t_{2p}$. These are shown in the right-hand panel of Fig. 1 with vertical dotted lines. At these times, the virial mass of the host halo is $1.6$ and $1.8 \times 10^{12} \, \text{M}_\odot$, respectively. At $t = t_{1p}(t_{2p})$, the satellite is at a distance of $65(69) \, \text{kpc}$, with the radial velocity $V_r = 78(89) \, \text{km s}^{-1}$ and the tangential velocity $V_t = 347(302) \, \text{km s}^{-1}$. In the analysis that follows we focus on the properties of LMCa and its associated subhaloes at $t_{1p}$ and $t_{2p}$.

These values are in reasonable agreement with the latest LMC measurements; in particular, the tangential speed at the first pericentre agrees within $1 \sigma$ with the results of Kallivayalil et al. (2006) and of Piatek et al. (2008). The velocities are lower by $\sim 15$ per cent at the second pericentre, mainly because the apocentre of the orbit has been reduced to $230 \, \text{kpc}$ from the $480 \, \text{kpc}$ reached at turnaround. This argument would appear to favour the first-pericentric interpretation for the LMC orbit, in tune with recent suggestions (see, e.g., Besla et al. 2007; Busha et al. 2010b; Boylan-Kolchin et al. 2011; Tollerud et al. 2011). We urge caution, however, with this interpretation. The actual pericentric speed will depend sensitively on the actual turnaround radius and on the mass of the Galaxy, both of which are rather uncertain. Furthermore, we do not expect an exact match between LMC and LMCa because of the limited statistics that the six Aquarius haloes allow. A more robust result seems to be that, because of the large pericentric distance, systems analogous to the LMC should experience a relatively moderate loss of orbital energy, allowing them to return to its second pericentre with the similar speed to the first. If LMCa had a slightly larger first-pericentre speed then quite possibly the second pericentre would have been in better agreement with the LMC than the first. We conclude that multiple passages cannot be confidently ruled out by this evidence alone.

3 RESULTS

3.1 The orbit of the LMCa group

The left-hand panel of Fig. 1 shows the radial evolution of LMCa and its 250 most massive associated subhaloes (identified at $t_d$ within the same friends-of-friends group). This shows the complex orbital behaviour of LMCa subhaloes as the group gets disrupted in the tidal field of the primary halo. As emphasized by Sales et al. (2007b) and Ludlow et al. (2009), many satellites undergo drastic changes in energy and angular momentum during the pericentric passage, causing some systems to achieve escape velocity and to leave the primary halo altogether.

Interestingly, the LMCa group itself contains captured ‘escapees’ from another group. As may be seen in the left-hand panel of Fig. 1,
were actually Aitoff projection of all particles belonging to the LMCa group at two different times, \( t_{1p} \) (near the first pericentre, left-hand panel) and \( t_{2p} \) (near second pericentre, right-hand panel), when the kinematics of the most massive LMCa member (shown by a green circle) matches best that of the LMC (see Fig. 1). Dots denote all individual particles within the virial radius of the LMCa at the time of identification, \( t_{id} \). Those coloured black are still bound to LMCa; grey are those that have become unbound as a result of the tidal interaction with the primary halo. Particles in red are those belonging to self-bound substructures of LMCa. The positions in the sky of all known MW satellites are also shown and labelled in blue. The orbital path of LMCa is shown by the dashed green curve; a magenta curve traces the location of the Magellanic Stream, taken from Nidever et al. (2010). The reference frame of the simulation has been rotated so that the position in the sky and the proper motion of LMCa match those of the LMC. Note how all particles and substructures associated with LMCa stretch along the orbital path. At \( t_{1p} \) (the left-hand panel) most associated subhaloes lie near the LMC since tidal stripping has not yet had enough time to disrupt the system. At \( t_{2p} \) (the right-hand panel) the particles and subhaloes associated with LMCa are more widely spread across the sky but still trace the orbital path. The LMCa footprint can be used, together with velocity information, to investigate whether other MW satellites have been associated with the LMC in the past. See the text for further details.

Figure 2. Aitoff projection of all particles belonging to the LMCa group at two different times, \( t_{1p} \) (near the first pericentre, left-hand panel) and \( t_{2p} \) (near second pericentre, right-hand panel), when the kinematics of the most massive LMCa member (shown by a green circle) matches best that of the LMC (see Fig. 1). Dots denote all individual particles within the virial radius of the LMCa at the time of identification, \( t_{id} \). Those coloured black are still bound to LMCa; grey are those that have become unbound as a result of the tidal interaction with the primary halo. Particles in red are those belonging to self-bound substructures of LMCa. The positions in the sky of all known MW satellites are also shown and labelled in blue. The orbital path of LMCa is shown by the dashed green curve; a magenta curve traces the location of the Magellanic Stream, taken from Nidever et al. (2010). The reference frame of the simulation has been rotated so that the position in the sky and the proper motion of LMCa match those of the LMC. Note how all particles and substructures associated with LMCa stretch along the orbital path. At \( t_{1p} \) (the left-hand panel) most associated subhaloes lie near the LMC since tidal stripping has not yet had enough time to disrupt the system. At \( t_{2p} \) (the right-hand panel) the particles and subhaloes associated with LMCa are more widely spread across the sky but still trace the orbital path. The LMCa footprint can be used, together with velocity information, to investigate whether other MW satellites have been associated with the LMC in the past. See the text for further details.

3.2 Position and kinematics of the LMCa group

We plot in Fig. 2 the position in the sky (in an Aitoff projection) of all particles identified at \( t_{id} \) to belong to LMCa. The panel on the left corresponds to the first pericentre, \( t_{1p} \), and that on the right to the second pericentre, \( t_{2p} \). The simulation reference frame has been rotated so that the position in the sky and the direction of the motion of the main LMCa subhalo (indicated by a green circle) coincide with those of the LMC. The orbital path is shown by a green dashed line; the line in magenta traces the Magellanic Stream (Nidever et al. 2010). Particles in black are those currently still bound to LMCa, and those in grey correspond to tidally stripped LMCa material. Particles in red highlight the LMCa substructures that remain self-bound.

Fig. 2 shows the complex footprint on the sky traced by LMCa and its debris, and how it changes substantially from the first to second pericentric passage. At first approach (the left-hand panel of Fig. 2), most LMCa subhaloes cluster around the LMC because tidal stripping has not yet had enough time to disrupt the system. Nevertheless, there are a few tidally stripped systems (those more loosely bound to LMCa at \( t_{id} \)), and they roughly trace the orbit of LMCa along a nearly polar circle. The sky is not uniformly populated by the stream; for example, because the pericentric passage occurs near the South Galactic Pole very few LMCa subhaloes have a chance of reaching the northern Galactic cap by \( t_{1p} \). Some systems stray from the orbital plane despite their previous association, but these cases are rare and correspond to subhaloes populating the outskirts of the LMCa group at \( t_{id} \).

The orbital path is still discernible in the tidal stream at the second pericentre, but the debris populates now both hemispheres in the sky. At this time, LMCa has lost more than 70 per cent of its original mass to tides, compared with only 40 per cent at \( t = t_{1p} \). The distribution of the debris on the sky would certainly be wider for a progenitor of larger mass than the one considered here.

Blue asterisks in Fig. 2 indicate the position of all known MW satellites, including the ultra-faint dwarfs discovered by the Sloan Digital Sky Survey (SDSS), which are located mainly in the northern Galactic cap (see Table 2 for the compilation of values used). Several dwarfs lie along the debris path and therefore could potentially have been associated with the LMC. These include, at \( t = t_{1p} \), Sextans (Sex), Dra, Segue 3 (Seg3), Pisces II (PiscII), Scl, Fornax (For), Tucana (Tuc), Car, Leo II and the SMC. Because the debris is more spread out at \( t_{2p} \), the list includes then further dwarfs, such as those in the constellation of Leo.
Of course, true association requires not only coincidence with the LMCa tidal stream in projection, but also in distance and velocity. We investigate this in Fig. 3, where we plot the Galactocentric distance and radial velocity of LMCa particles for $t = t_{1p}$ (left) and $t = t_{2p}$ (right). Colour coding is the same as in Fig. 2. Data for all known MW satellites (as listed in Table 2) are also shown in each panel, for comparison. Since the LMCa debris is confined to specific regions in the $(r, V_r)$ plane, these data may be used to test the association of any individual dwarf with the LMC, subject to assuming that the LMC is either on its first or second approach to the Galaxy. We explore these associations next.

### 3.3 Association with the Clouds

To be deemed an ‘LMC associate’ a satellite must satisfy at least the following three conditions: (i) it should fall in the celestial sphere within the footprint of the LMCa group; (ii) it should be at a Galactocentric distance consistent with that of LMCa particles at the same location in the sky and (iii) it should have Galactocentric radial velocity also consistent with LMCa in the same region. In principle, a further condition involving the tangential velocity could be added to the list, but the preliminary nature of most proper motion estimates for MW satellites implies that the results are unlikely to be conclusive at this stage (see the Appendix for more details). We discuss conditions (i) to (iii) below.

#### 3.3.1 Sky proximity

We can quantify the proximity in the sky of any dwarf to the LMCa stream by computing the angular distance to the $n$th nearest LMCa particle in projection and comparing that with the probability of obtaining a similar distance (or smaller) for a random point in the sky. Note that the analysis that follows uses all LMCa particles (rather than just subhaloes) when comparing with the MW satellites, since this provides a more complete sampling of the distribution in phase space expected for LMC debris.

The histograms in Fig. 4 show the distribution of the angular distance to the $50$th nearest LMCa particle, $\delta_{50}$, for 10 000 random points in the celestial sphere; the median of the distribution is at $\delta_{\text{lim}} = 4^\circ$ and $\delta_{\text{lim}} = 2^\circ$ for the first and second pericentre passages, respectively. As may be seen from the insets in Fig. 4 the footprint of the LMCa stream is traced faithfully by regions satisfying $\delta_{50} < \delta_{\text{lim}}$ (shown in red) and we shall use this condition to decide which dwarfs are likely to be associated with the LMC.

According to Fig. 4, at the first pericentre only eight dwarfs satisfy the proximity condition specified above but, because the LMCa footprint covers a much larger fraction of the sky at the second pericentre, 17 dwarfs pass this constraint then. These numbers are reasonably insensitive to our choice of $n = 50$, especially at the first pericentre; choosing the 100th nearest neighbour results in nine likely associated dwarfs at $t_{1p}$ and 22 at $t_{2p}$.

#### 3.3.2 Radial velocity

Figs 5 and 6 are then used to check which of these candidate dwarfs are also associated with the stream in distance and velocity. The various panels in these figures show the Galactocentric distance and radial velocity of each of the dwarfs in the LMCa sky footprint, together with those of all LMCa particles closer than $\delta_{\text{lim}}$ in the sky from each dwarf. This enables an intuitive test of which satellites have distances and velocities consistent with LMC association.

For example, the top left-hand panel of Fig. 5 corresponds to the SMC and it shows that there are plenty of LMCa particles with distances and radial velocities coincident with the SMC at the first approach, endorsing a true association between the LMC and the SMC. An opposite example is provided by Dra; the data in Fig. 5 show that, although it is within the LMCa footprint, all of the particles associated with LMCa at Dra’s location have discrepant velocities and/or distances. This is because Dra is projected on to the...
Figure 4. Distribution function of $\delta_{50}$, the angular size (radius) of the circle that contains the 50 nearest LMCa particles in projection, computed for 10,000 random points in the celestial sphere. Left- and right-hand panels correspond to $t = t_{1p}$ and $t_{2p}$, respectively. $\delta_{50}$ is a useful measure of proximity to the LMCa stream in the sky for any given point. In the inserted Aitoff maps, red is used to highlight points with $\delta_{50} < \delta_{\text{lim}}$, where $\delta_{\text{lim}}$ is the median of the random distribution. Black points correspond to $\delta_{50} > \delta_{\text{lim}}$. As demonstrated by the Aitoff insets, $\delta_{50}$ is a useful measure of association with the stream. We show in each panel the values of $\delta_{50}$ corresponding to each MW dwarf, and retain only those with $\delta_{50} < \delta_{\text{lim}}$ as potentially associated with the LMC.

Figure 5. Galactocentric radial velocity and distance for dwarfs (filled squares) deemed possibly associated with the LMC according to the criterion of Fig. 4, i.e. $\delta_{50} < \delta_{\text{lim}}$ at $t = t_{1p}$. Each panel also shows the $r$ and $V_r$ of all LMCa particles (dots) within a circle of radius $\delta_{\text{lim}}$ centred at the position of each dwarf. This probes graphically whether the positional association indicated by proximity to the stream in the sky is corroborated by the velocity data. This test indicates that the SMC is the only known satellite clearly associated with the LMC if the Clouds are on their first pericentric approach. Aside from the SMC only Car and For seem marginally consistent with an LMC association. On the other hand, this test seems to rule out a possible association for all other candidates.
trailing stream at the first pericentre, and one would expect then very large negative radial velocities at Dra’s Galactocentric distance. A similar analysis may be carried out for each dwarf individually, but it should be clear from Fig. 5 that, aside from the SMC, only Car and For seem to have a reasonable chance of being associated with the Clouds if they are on the first approach.

The situation is less clearcut at the second pericentre because the LMCa footprint is larger, and because the stream now has multiple wraps, which allows for a wider range of velocities in a given direction in the sky to be consistent with LMCa association. The right-hand panel of Fig. 4 indicates that 17 dwarfs pass the sky proximity test; these are shown (two per panel except in the middle-left) in Fig. 6. Inspection of each panel shows that, aside from the SMC, Car, Canes Venatici II, Scl, Leo II, Leo IV and Leo V could in principle be associated with the LMC. The situation of For, Canes Venatici I and Sex is less clear but one would be hard pressed to rule out an association in such cases. Bootes (I and II), Seg3, LeoT, Willman I and Coma are all unlikely to be associated with the LMC.

3.3.3 Orbital angular momentum

The sky proximity and radial velocity constraints discussed above are sensitive to the fact that we consider here a single LMC look-alike system. This is compounded by the relatively low mass of LMCa, compared with the $1.3 \times 10^{11} M_\odot$ suggested by the abundance-matching analysis of Boylan-Kolchin et al. (2011). A more massive subhalo may leave a broader footprint on the sky and lead to a wider range of radial velocities consistent with LMC-associated debris. More conclusive statements about the likelihood of the association of the candidate satellites identified in the previous subsections require accurate measurements of the proper motion in order to constrain their tangential velocity and to verify that they follow orbits roughly aligned with the orbital plane of the LMC. Indeed, as we show below, the direction of the orbital angular momentum of a dwarf might be one of the cleanest tests of association with the Clouds.

This is shown in Fig. 7, where we show, in an Aitoff projection of Galactocentric coordinates ($l_G$, $b_G$), the direction of the orbital angular momentum of LMCa and its associated substructures at the first and second pericentric passages. Because of the nearly polar orbit the direction of the angular momentum of most LMCa-associated material is roughly on the Galactic plane, pointing in the direction of the Sun from the Galactic centre, i.e. $l_0 = 180^\circ$, $b_0 = 0^\circ$. This tight alignment is preserved at the second approach, albeit with larger scatter.

In Galactocentric Cartesian coordinates, with the $X$-axis pointing away from the Sun, the $Y$-axis defined positive in the direction of Galactic rotation and the $Z$-axis defined positive in the direction of the Galactic North Pole; this implies that the $X$-component of the orbital angular momentum ($j_X$) of associated satellites should be negative and much larger in magnitude than $j_Y$ or $j_Z$. This may
...LMCa turns around from a distance \( t = -0.02 \) and \( t = 0.08 \), respectively. Note that, because of the nearly polar orbit of LMCa, the angular momentum points in all cases in the \(-X\) direction, i.e. to the Sun from the Galactic centre. The angular momentum direction is also listed for satellites with published proper motions (third row) and may be used to assess their possible association with the Clouds.

### Table 1. Cartesian components of the unit vector that characterizes the direction of the (average) angular momentum of LMCa particles near each candidate LMC-associated satellite, according to the discussion of Figs 5 and 6.

| Name    | Time   | \( j_x \)     | \( j_y \)     | \( j_z \)     |
|---------|--------|---------------|---------------|---------------|
| LMC     | \( t = t_{1p} \) | \(-0.97 \pm 0.03\) | \(0.14 \pm 0.07\) | \(-0.19 \pm 0.10\) |
|         | \( t = t_{2p} \) | \(-0.97 \pm 0.03\) | \(0.14 \pm 0.06\) | \(-0.18 \pm 0.09\) |
|         | obs    | \(-0.97 \pm 0.01\) | \(0.14 \pm 0.02\) | \(-0.18 \pm 0.03\) |
| SMC     | \( t = t_{1p} \) | \(-0.92 \pm 0.05\) | \(0.04 \pm 0.10\) | \(-0.35 \pm 0.08\) |
|         | \( t = t_{2p} \) | \(-0.90 \pm 0.05\) | \(0.05 \pm 0.17\) | \(-0.38 \pm 0.10\) |
|         | obs    | \(-0.91 \pm 0.05\) | \(0.08 \pm 0.11\) | \(-0.39 \pm 0.09\) |
| Car     | \( t = t_{1p} \) | \(-0.93 \pm 0.12\) | \(0.25 \pm 0.07\) | \(-0.04 \pm 0.20\) |
|         | \( t = t_{2p} \) | \(-0.95 \pm 0.03\) | \(0.25 \pm 0.06\) | \(-0.01 \pm 0.15\) |
|         | obs    | \(-0.40 \pm 0.48\) | \(0.46 \pm 0.18\) | \(-0.79 \pm 0.38\) |
| For     | \( t = t_{1p} \) | \(-0.92 \pm 0.20\) | \(0.19 \pm 0.11\) | \(0.20 \pm 0.07\) |
|         | \( t = t_{2p} \) | \(-0.77 \pm 0.04\) | \(0.63 \pm 0.05\) | \(0.00 \pm 0.03\) |
|         | obs    | \(-0.94 \pm 0.06\) | \(0.00 \pm 0.41\) | \(0.04 \pm 0.05\) |
| Scl     | \( t = t_{1p} \) | \(-0.86 \pm 0.03\) | \(-0.50 \pm 0.04\) | \(0.003 \pm 0.005\) |
|         | \( t = t_{2p} \) | \(-0.97 \pm 0.02\) | \(0.17 \pm 0.13\) | \(-0.03 \pm 0.09\) |

be seen in Table 1, which lists the components of the unit vector identifying the direction of the (average) angular momentum of particles associated in the sky with the candidate dwarfs identified in the previous subsection. Note that, with no exception, the angular momentum points clearly towards \(-X\), the anti-Galactic centre direction.

This result makes strong predictions regarding the tangential velocity of the candidate satellites, which can be checked against observation for the few satellites with available proper motions (SMC: Kallivayalil et al. 2006; Carina: Piatek et al. 2003; Fornax: Piatek et al. 2007 and Sculptor: Piatek et al. 2006). Inspection of Table 1 and Fig. 7 shows, that of the four satellites with published spatial velocities, only the SMC appears to be associated with the LMC. None of the other three (Car, For and Scl) seems obviously associated with the Clouds according to this test (see the last three columns of Table 2).

In hindsight this is not entirely surprising, given the very dissimilar chemical enrichment patterns and gas content of the LMC and SMC compared with other Galactic satellites (Mateo 1998; Carrera et al. 2008; Harris & Zaritsky 2009; Kirby et al. 2011a,b). Explaining what drives the diversity in star formation history, metal enrichment and gas fractions of Galactic satellites remains a prime challenge for dwarf galaxy formation models. We hasten to add, however, that as the recent revision to the proper motion of the LMC illustrates (Kallivayalil et al. 2006), proper motion measurements are exceedingly difficult, and hence our conclusion should be revisited when new, more accurate data become available.

## 4 SUMMARY AND CONCLUSIONS

We use cosmological \(N\)-body simulations from the Aquarius Project to study the orbit of the LMC and its possible association with the SMC and other MW satellites in light of new proper motion data (Kallivayalil et al. 2006; Piatek et al. 2008). We search the simulations for LMC dynamical analogues, i.e. accreted subhaloes with the pericentric distance (\(\sim 50\) kpc) and velocity (\(\sim 400\) km s\(^{-1}\)) matching those of the Clouds.

One suitable candidate (LMCa) is a \(3.6 \times 10^{10}\) M\(_{\odot}\) system accreted at \(z \sim 0.5\) (\(t = 8.7\) Gyr) by Aq-A, a halo that at \(z = 0\) has a virial mass of \(1.8 \times 10^{12}\) M\(_{\odot}\). LMCa turns around from a distance of \(480\) kpc at \(t_{1p} \sim 5\) Gyr (\(z = 1.3\)), accretes into the MW halo at \(t = 8.6\) Gyr (\(z = 0.5\)) and completes two pericentric passages by \(z = 0\).

We use the positions and velocities of particles belonging to LMCa before infall in order to trace the orbital evolution of LMC-associated satellites and to inform the analysis of the likelihood...
that other MW satellites were accreted in association with the Magellanic Clouds. Our main conclusions may be summarized as follows.

Near each pericentric passage the kinematic properties of LMCa match approximately those of the LMC. This implies that (i) the orbit of the LMC is not particularly unusual given the halo virial mass, and that (ii) it is difficult to decide, using only kinematical data, whether the LMC is on the first approach or has already completed a full orbit.

If the LMC is on the first approach, then most of its associated subhaloes should be tightly clustered around its location. Although rare, some LMC-associated systems may still be found well away from the LMC but along the orbital path of the group. Since none of them has completed a single orbit there are strong position–radial velocity correlations that may be used to identify which satellites might have been accreted together with the LMC.

Of the known MW satellites only the SMC is clearly associated with the LMC. A case can also be made for For, Car and Scl, but it is not a particularly compelling one. This is especially true when considering available proper motion data, which suggest that the orbital planes of these three satellites are not aligned with that of the Clouds.

If the LMC is near its second pericentre then several further dwarfs qualify for association. Leo II, Leo IV and Leo V, in particular, show strong spatial and velocity coincidence with the tidal debris from LMCa, making them prime candidates for past association with the LMC. Persuasive, but hardly conclusive, cases can also be made for a handful of other dwarfs, such as Canes Venatici II and Leo I. These tentative associations may be firmed up or refuted using the full spatial velocity, for which our simulations make a strong prediction: it must be such that the direction of the orbital angular momentum should point unambiguously in the anti-Galactic centre direction.

We then expect few, if any, known MW satellites to be associated with the Clouds, especially if they are on the first approach. The simulations, however, make a very clear prediction in that case: most satellites associated with the Clouds have yet to disperse and should therefore be very near them. How many could we expect? The number depends strongly on the virial mass of the Clouds and is, therefore, highly uncertain. If the mass is as high as $1.3 \times 10^{11} \, M_\odot$, as

| Name          | $M_\star$ (mag) | $l$ (°) | $b$ (°) | $r$ (kpc) | $V_r$ (km s$^{-1}$) | Refs. | Test             | Test         | Test         |
|---------------|----------------|--------|--------|----------|----------------|------|-----------------|--------------|--------------|
| LMC           | −18.5          | 280.5  | −32.9  | 49.4     | 87.0           | 1    | Sky proximity   | Radial velocity | Angular momentum |
| SMC           | −17.1          | 302.8  | −44.3  | 57.2     | 11.4           | 1    | √               | √            | √            |
| Sc1           | −9.8           | 287.5  | −83.2  | 90.1     | 78.1           | 1    | √               | ×            | −            |
| For           | −13.1          | 237.1  | −65.7  | 142.1    | −33.7          | 1    | √               | √            | √            |
| Car           | −9.4           | 260.1  | −22.2  | 101.7    | 13.3           | 1    | √               | ×            | ×            |
| Leo I         | −11.9          | 226.0  | 49.1   | 254.0    | 181.9          | 1    | ×               | −            | −            |
| Sex           | −9.5           | 243.5  | 42.3   | 93.2     | 78.6           | 1    | √               | ×            | ×            |
| Leo II        | −10.1          | 220.2  | 67.2   | 212.7    | 23.4           | 1    | ×               | −            | −            |
| Ursa Minor    | −8.9           | 105.0  | 44.8   | 62.1     | −89.8          | 1    | ×               | ×            | −            |
| Dra           | −8.6           | 86.4   | 34.7   | 80.0     | −103.8         | 1    | √               | ×            | ×            |
| Sagittarius   | −13.8          | 5.6    | −14.1  | 21.9     | 171.9          | 1    | √               | ×            | −            |
| Tuc           | −10.0          | 322.9  | −47.3  | 475.5    | 38.0           | 1    | √               | ×            | −            |
| Ursa Major I  | −5.6           | 159.4  | 54.4   | 110.9    | −8.8           | 2    | ×               | ×            | −            |
| Ursa Major II | −3.8           | 152.4  | 37.4   | 38.5     | −36.6          | 2    | ×               | ×            | −            |
| Canes Venatici I | −7.9       | 74.3   | 79.8   | 219.8    | 76.9           | 2    | ×               | −            | −            |
| Canes Venatici II | −4.8       | 113.6  | 82.7   | 151.7    | −96.2          | 2    | ×               | −            | −            |
| PscII         | −5.0           | 79.2   | −47.1  | −        | 202.4          | 3    | ×               | ×            | −            |
| Seg1          | −3.0           | 220.5  | 50.4   | 28.1     | 116.3          | 2.4  | ×               | ×            | −            |
| Seg2          | −2.5           | 149.4  | −38.1  | 41.2     | 40.1           | 5    | ×               | ×            | −            |
| Seg3          | −1.2           | 69.4   | −21.2  | −        | 209.7          | 3    | ×               | ×            | −            |
| Coma          | −3.7           | 241.9  | 83.6   | 45.2     | 83.9           | 2.4  | ×               | ×            | −            |
| Hercules      | −6.0           | 28.7   | 36.9   | 132.2    | 142.9          | 4    | ×               | −            | −            |
| Leo IV        | −5.1           | 265.4  | 56.5   | 158.6    | 14.0           | 4    | ×               | −            | −            |
| Bootes        | −5.8           | 358.1  | 69.6   | 63.5     | 107.4          | 6    | ×               | −            | −            |
| Bootes II     | −2.7           | 353.7  | 68.8   | 44.7     | −117.3         | 7    | ×               | ×            | −            |
| Leo T         | −7.1           | 214.8  | 43.6   | 422.1    | −56.0          | 8    | ×               | −            | −            |
| Willman I     | −2.7           | 158.5  | 56.7   | 484.4    | 34.2           | 9    | ×               | ×            | −            |
| Leo V         | −4.3           | 261.9  | 58.5   | 180.8    | 62.3           | 10   | ×               | −            | −            |

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suggested by the abundance-matching analysis of Boylan-Kolchin et al. (2011), then we would expect it to have subhaloes of order 7 with peak circular velocities exceeding 20 km s^{-1} (Springel et al. 2008). This, according to the recent model of Font et al. (2011), is the minimum halo potential depth required to host a luminous dwarf.

Although the numbers seem modest, one may be encouraged by the fact that the LMC does have at least one companion (the SMC), so the possibility that they are part of a larger ‘Magellanic Galaxy’ should not be dismissed too quickly. Surveys designed to target the sky around the LMC (SkyMapper,2 MAPS: Nidever et al. 2011; NOAO Outer Limit Survey; Saha et al. 2010) should help to unravel the history of the LMC and its companions. The surroundings of the Clouds might be hiding a trove of new MW satellites awaiting discovery.

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APPENDIX A: MAGELLANIC GALAXY-DEBRIS IN THE LMC FRAME

For completeness, Fig. A1 shows the distance–velocity plane of LMCa debris in a coordinate system centred at the LMC. As the system orbits within the host potential, mass is lost to tides and the
Figure A1. Total 3D velocity, $V_{LMC}^{3D}$, versus distance $r_{LMC}$, where the superscripts indicate that they are computed with respect to the LMC centre. Colour coding is the same as in the previous figure. The green asterisk shows the position of the SMC in this plane according to data from Kallivayalil et al. (2006). The transition from black (bound) to grey (unbound) dots can be used to infer the instantaneous escape velocity of the LMCa system. For comparison, blue curves show $V_{esc}$ for an NFW halo with the mass of LMCa at the time of infall, $M_{200} = 3.6 \times 10^{10} M_\odot$, assuming two different concentrations $c = 10, 20$. The effect of tides due to the host potential can be seen from the comparison between these curves and the velocity of the bound (black) particles; in particular, the mass-loss experienced between the first and second approaches is reflected by the smaller area (and lower velocities) covered by black particles in the right-hand panel (second pericentre) compared to the left (first pericentre).

Material initially associated with the LMC group gets progressively unbound. Substructures that remain bound to the LMC are shown in black and unbound material in grey. LMCa substructures are shown in red. The SMC falls in the ‘unbound’ region at either first or second pericentre, which suggests that the LMC–SMC might no longer be a bound pair. This conclusion, however, is sensitive to the mass of LMCa which, as discussed in the text, is likely smaller than the true LMC mass. Once reliable three-dimensional velocities become available for more dwarf galaxies, their distribution in the LMC-centred phase space may be used to place further constraints on their association with the Clouds.

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